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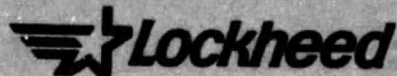
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(NASA-CR-171000) SPACE SHUTTLE MAIN ENGINE
POWERHEAD STRUCTURAL MODELING, STRESS AND
FATIGUE LIFE ANALYSIS. VOLUME 2: DYNAMICS
OF BLADES AND NOZZLES SSME HEFTP AND HPOTP
Final Report (Lockheed Missiles and Space

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SPACE SHUTTLE MAIN ENGINE
POWERHEAD STRUCTURAL MODELING,
STRESS AND FATIGUE LIFE ANALYSIS


VOLUME II — DYNAMICS OF BLADES
AND NOZZLES SSME HPFTP
AND HPOTP

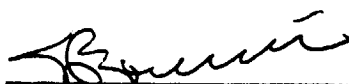
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Contract NAS8-34978

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FOREWORD

This report summarizes the results of work performed on Contract NAS8-34978. The work was performed by personnel of the Product Engineering & Development Section of Lockheed's Huntsville Research & Engineering Center, for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama. The Contracting Officer's technical representative for this study is Mr. Norman C. Schlemmer, Structures and Propulsion Laboratory, Engineering Analysis Division, Stress Analysis Branch (EP46).

This report is divided into four volumes with a section covering one aspect of analysis for all components and loads, and a fourth section for investigation of unscheduled events and special tasks undertaken during the effort. The volumes are:

- Volume I - Gasdynamic Environment of the SSME HPFTP and HPOTP Turbines, LMSC-HREC TR D867333-I.
- Volume II - Dynamics of Blades and Nozzles - SSME HPFTP and HPOTP, LMSC-HREC TR D867333-II.
- Volume III - Stress Summary of Blades and Nozzles at FPL and 115 percent RPL Loads SSME HPFTP and HPOTP Blades and Nozzles, LMSC-HREC TR D867333-III.
- Volume IV - Summary of Investigation of Unscheduled Events and Special Tasks, LMSC-HREC TR D867333-IV.

It should be noted that this report summarized our findings. A great body of data exists in the form of computer printout and magnetic tapes and is available to any interested reader for either amplification of the summarized data or as a basis for further work.

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1. INTRODUCTION

The objective of this phase of the analysis was to define normal modes of the blades and nozzles of the HPFTP and HPOTP and to identify potential driving forces for the blades. No attempt was made to identify nozzle drivers due to the lack of definition of these potential forces. These are expected in future analysis.

Section 2 describes the computer models used in blade analyses, with results. Section 3 gives similar information for the nozzles.

2. SSME TURBOPUMP BLADES

Section 2.1 describes the computer models used for this analysis and provides a guide for the reader in following the subsequent results, shown in Sections 2.2 through 2.5.

2.1 SSME BLADES - MODEL DESCRIPTION

Four NASTRAN models were constructed to simulate the first and second stage turbine blades of the HPFTP and the HPOTP. The general approach to modeling of all four models is the same making use of eight-node solid elements to represent the turbine blade geometry. Figures 2-1 through 2-4 show computer generated plots and specifications of each turbine blade model. The series of figures following these plots gives more specific information pertaining to grid and element locations. The models are defined in a rectangular coordinate system with Z radially outward and X in the direction opposite of gas flow. The turbine blades were modeled in their entirety with the exception of the "fir tree" on each blade which was not modeled to avoid additional size and complexity. The models were constrained at the base of the shank in all directions in order to simulate the rotor disk.

The models were executed to extract the normal mode frequencies and to plot the mode shapes. Tabular listings of frequencies for each turbine blade as well as Campbell diagrams and plots of the mode shapes for the first 10 modes are contained in Sections 2.2 through 2.5.

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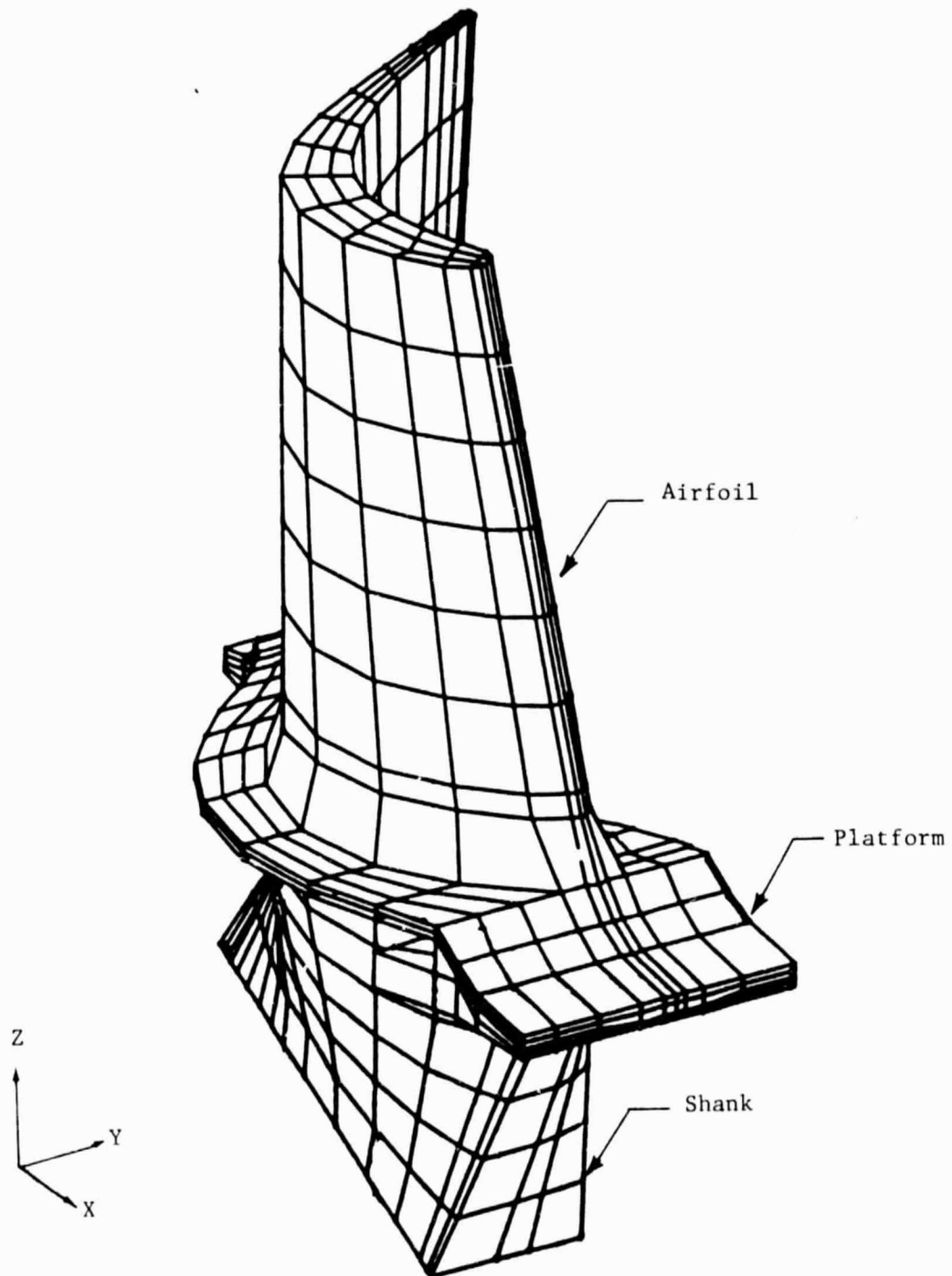


Fig. 2-1a HPFTP First Stage Turbine Blade (F-1) NASTRAN Model
(1575 Nodes, 1025 Elements)

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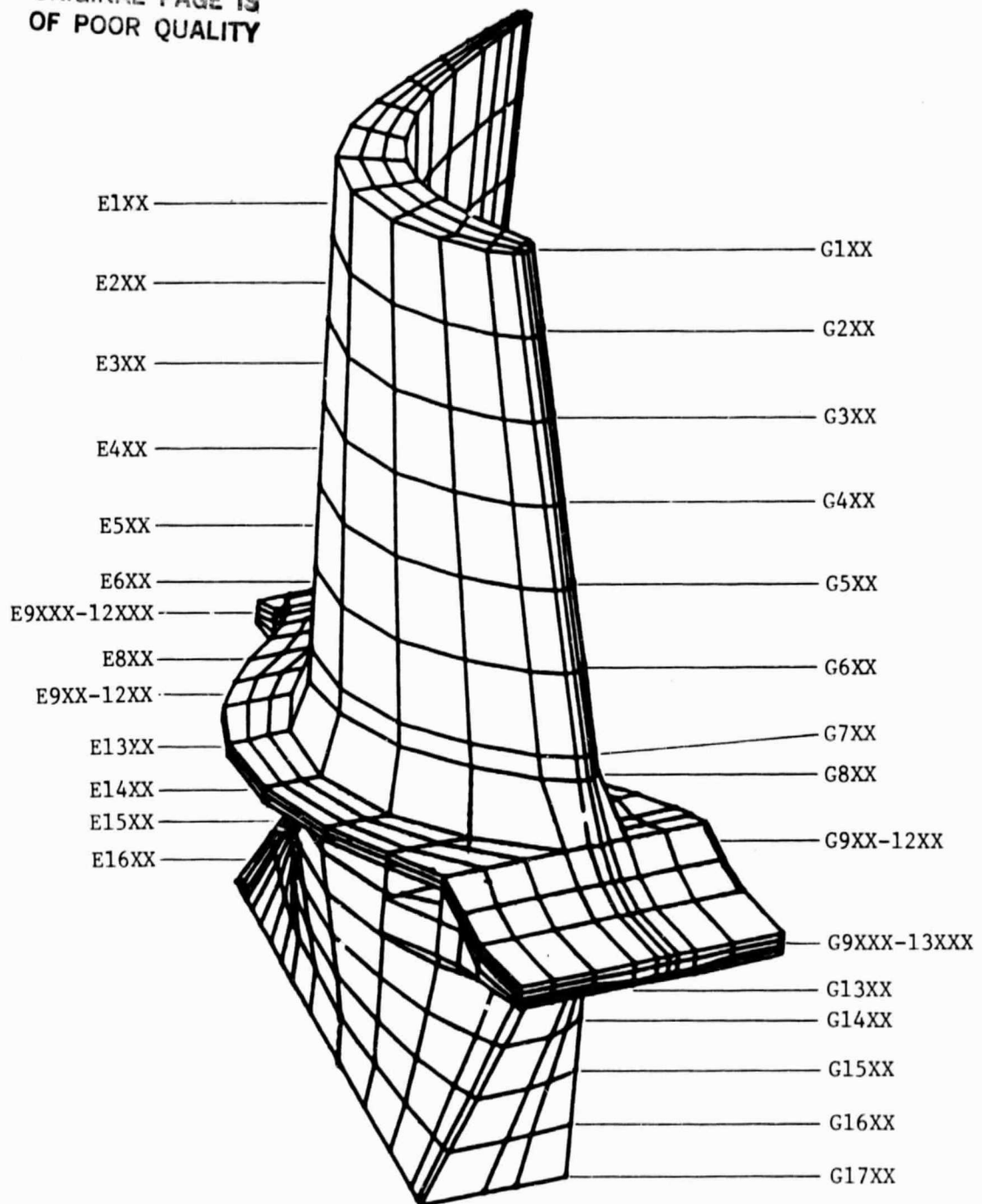


Fig. 2-1b F-1 Element and Grid Prefixes

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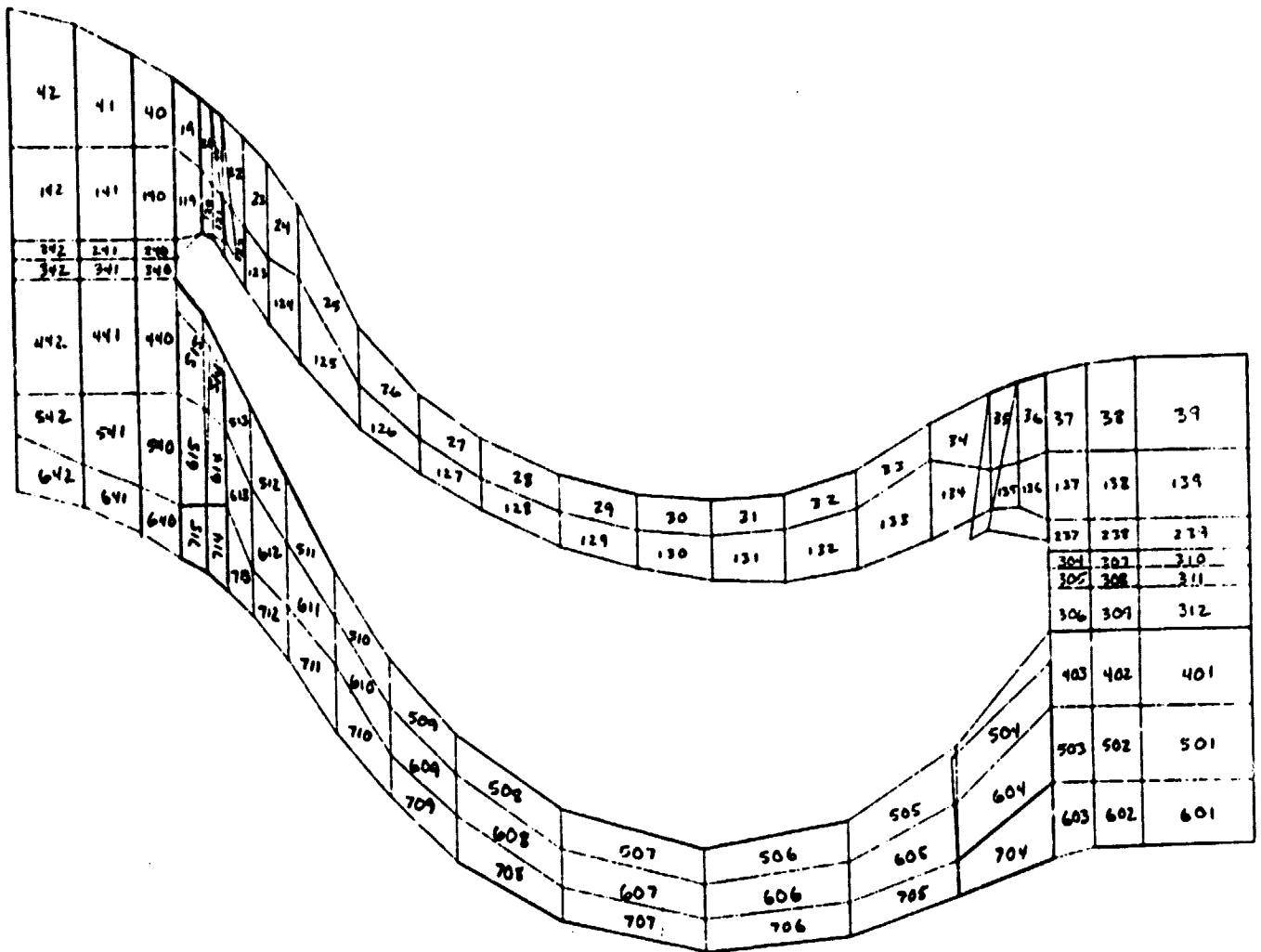


Fig. 2-1c F-1 Platform Element Layout

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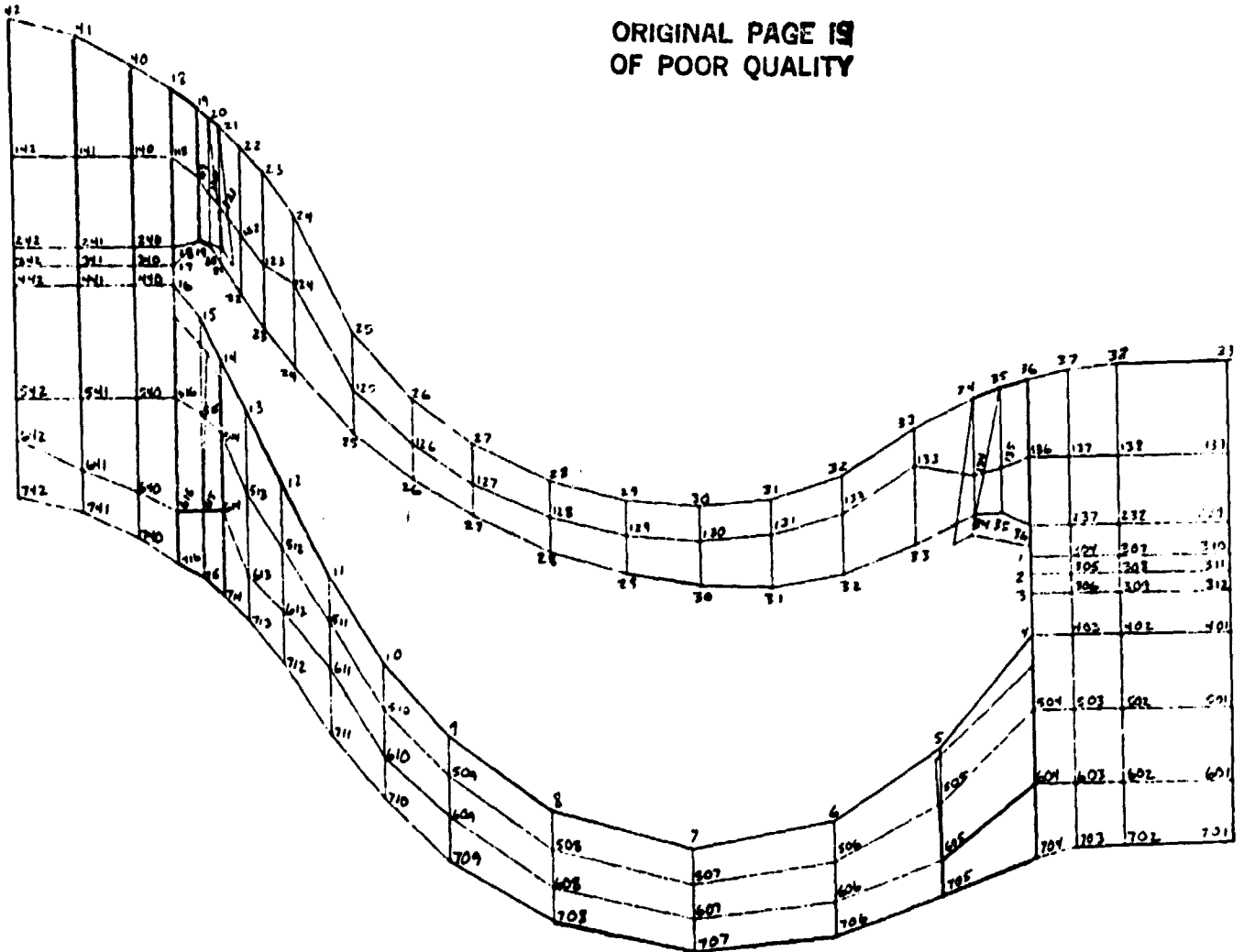


Fig. 2-1d F-1 Platform Grid Layout

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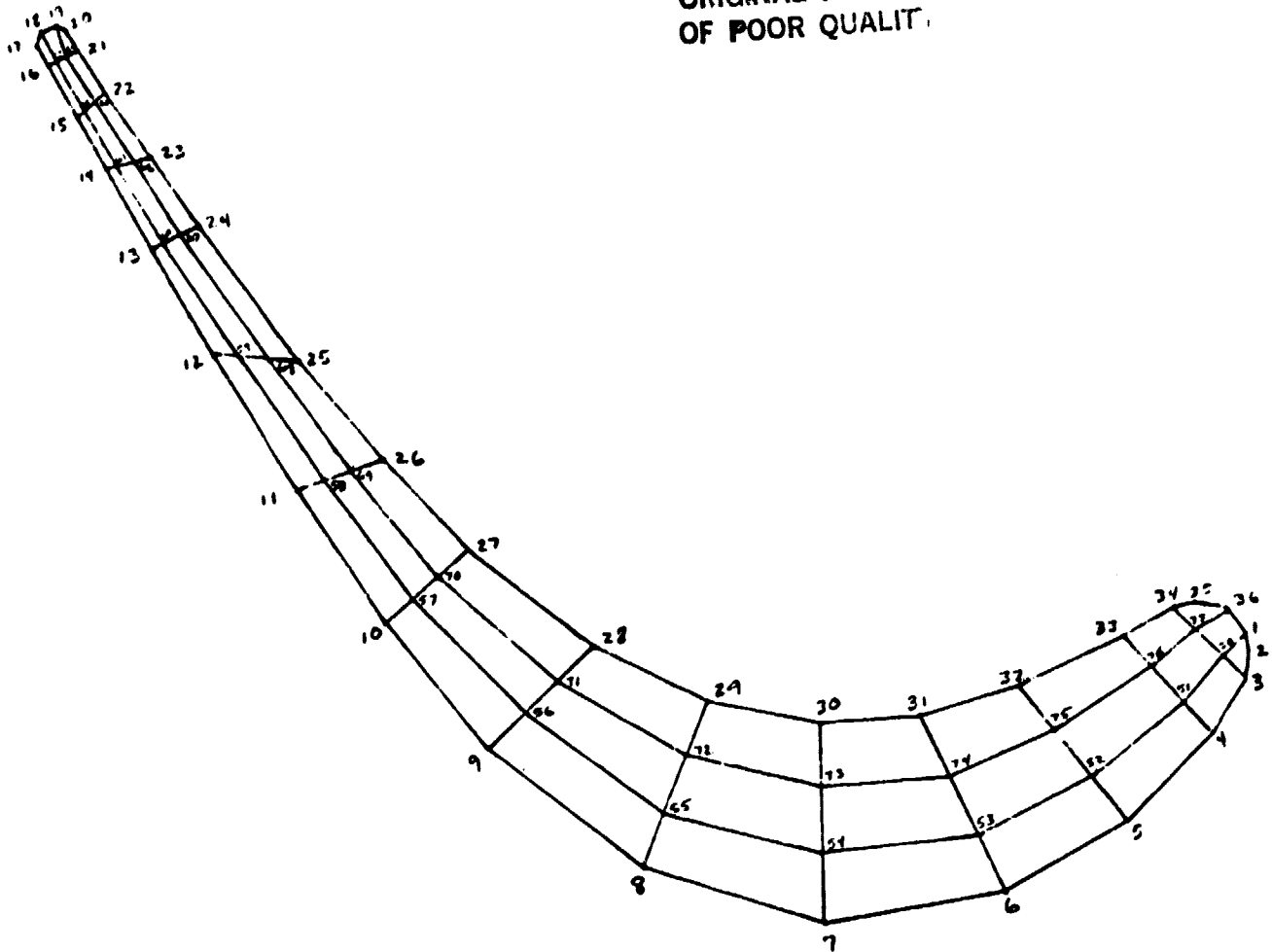


Fig. 2-1e F-1 Airfoil/Shank Grid Layout

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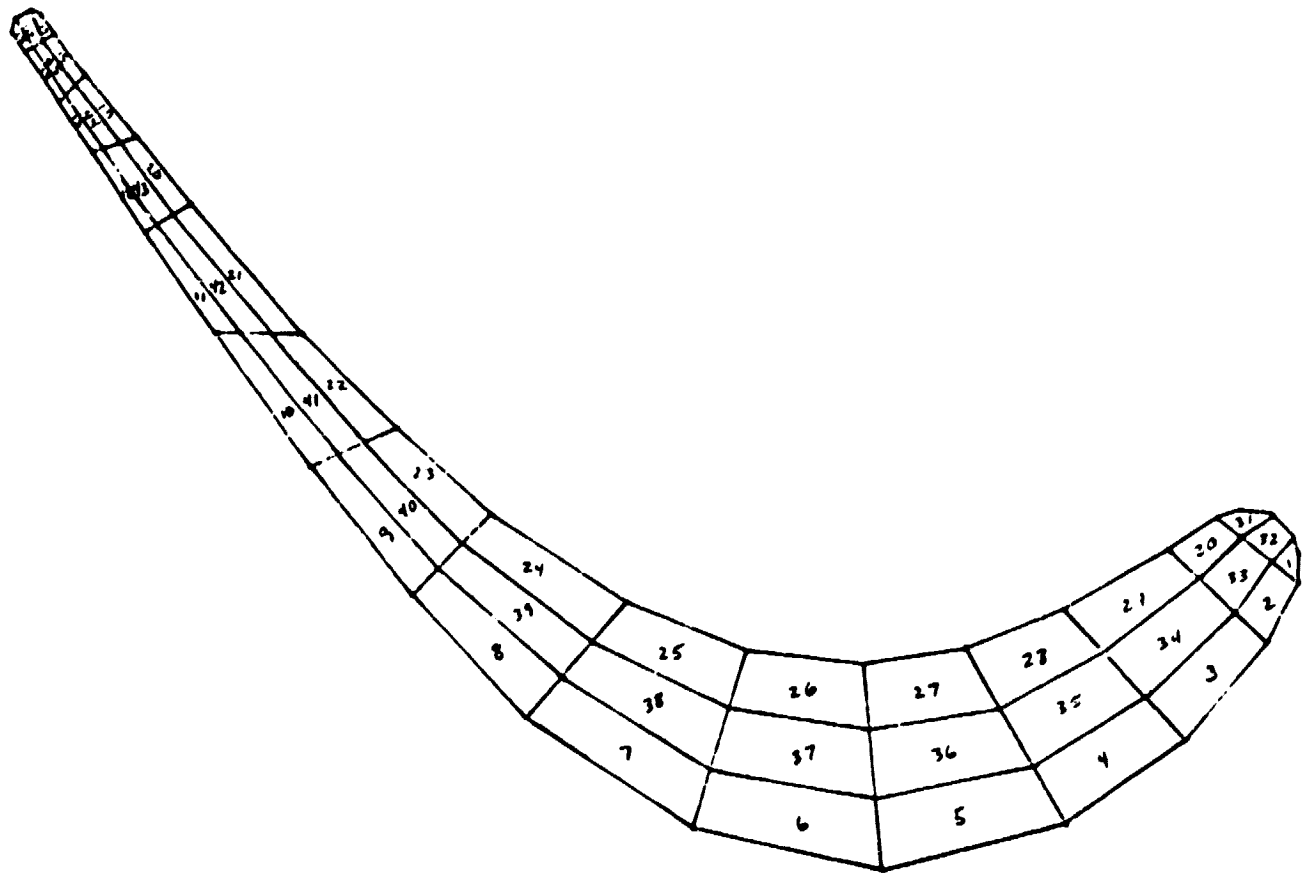


Fig. 2-1f F1 Airfoil/Shank Element Layout

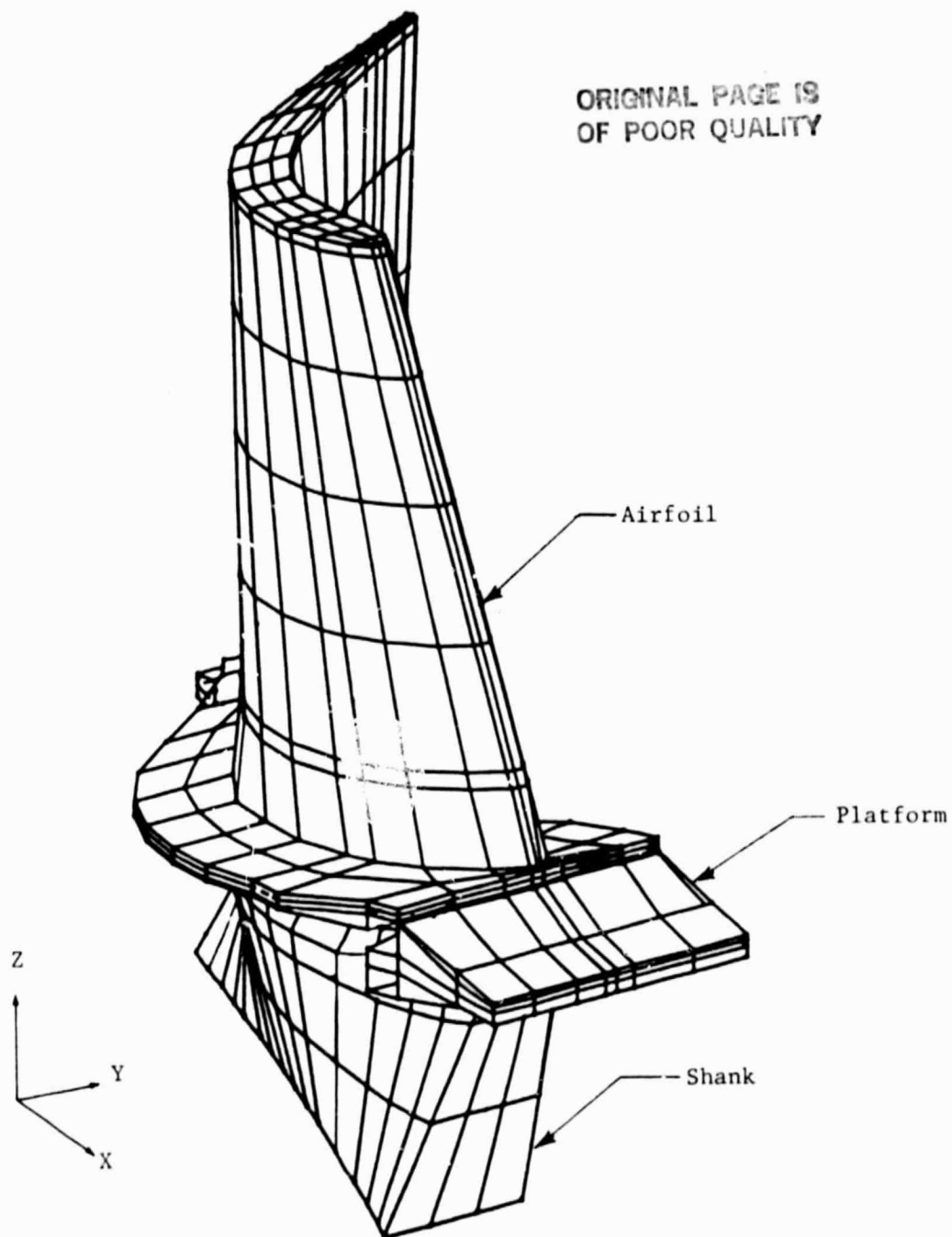


Fig. 2-2a HPFTP Second Stage Turbine Blade (F-2) NASTRAN Model
(1733 Nodes, 1185 Elements)

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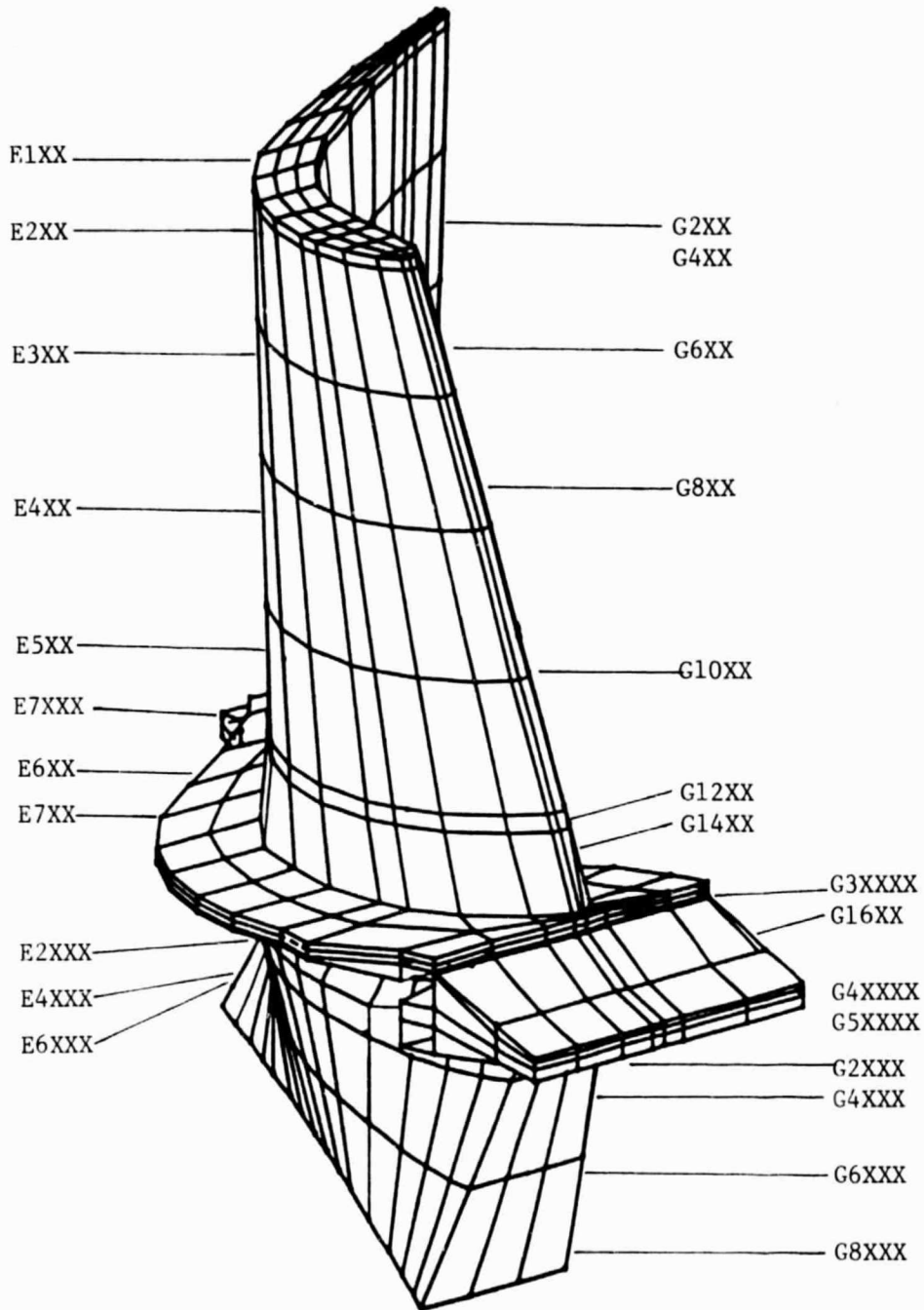


Fig. 2-2b F-2 Element and Grid Prefixes

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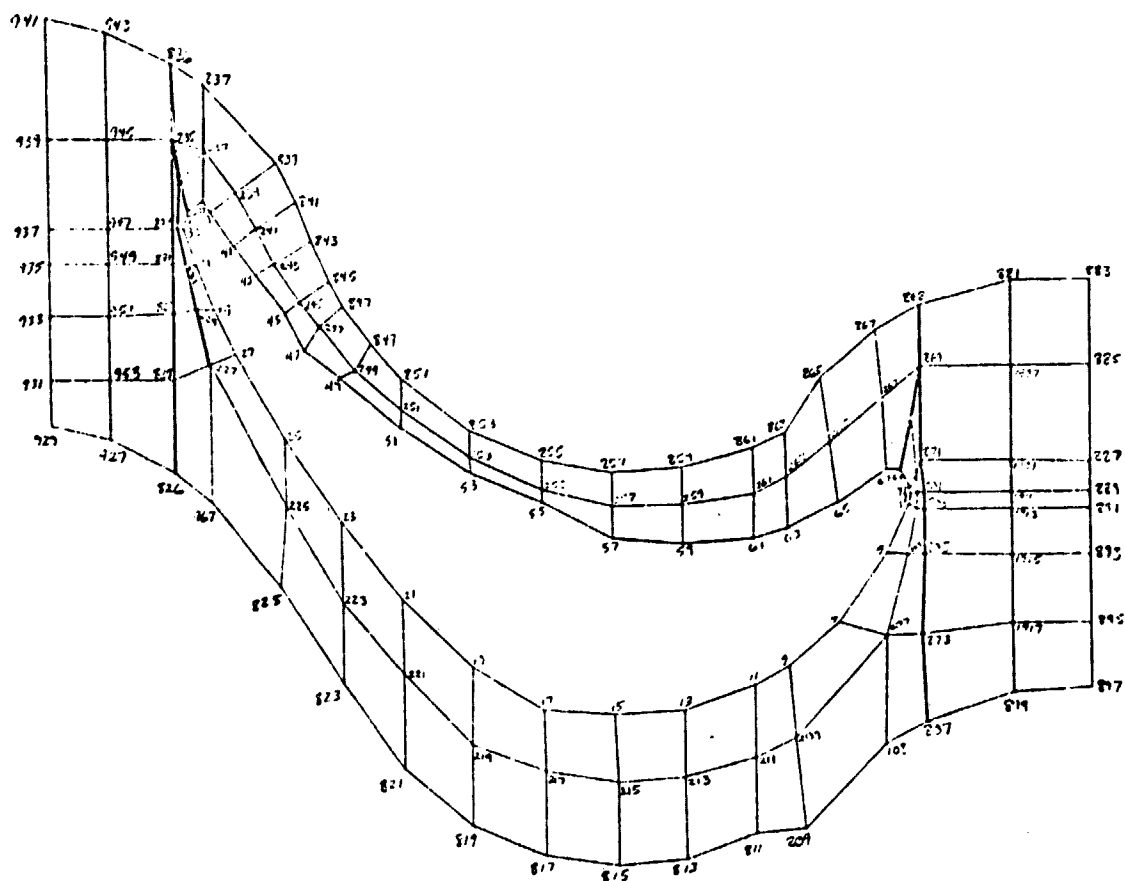


Fig. 2-2c F-2 Platform Grid Layout

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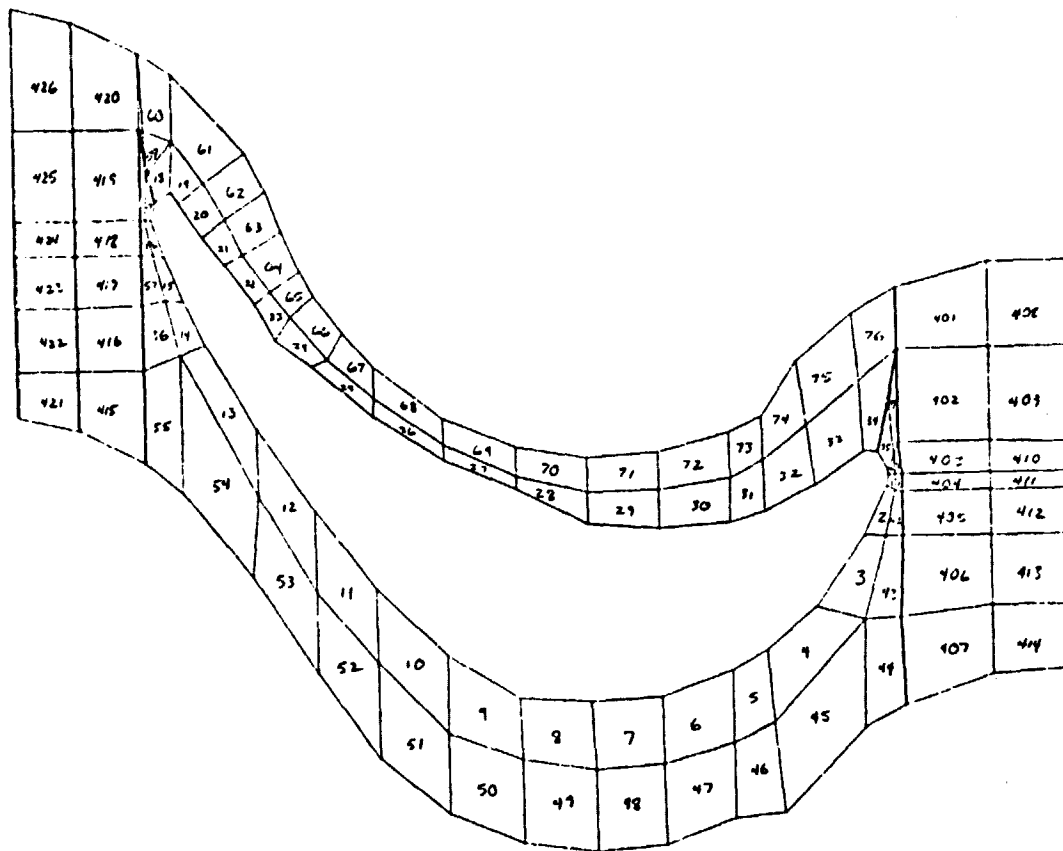


Fig. 2-2d F-2 Platform Element Layout

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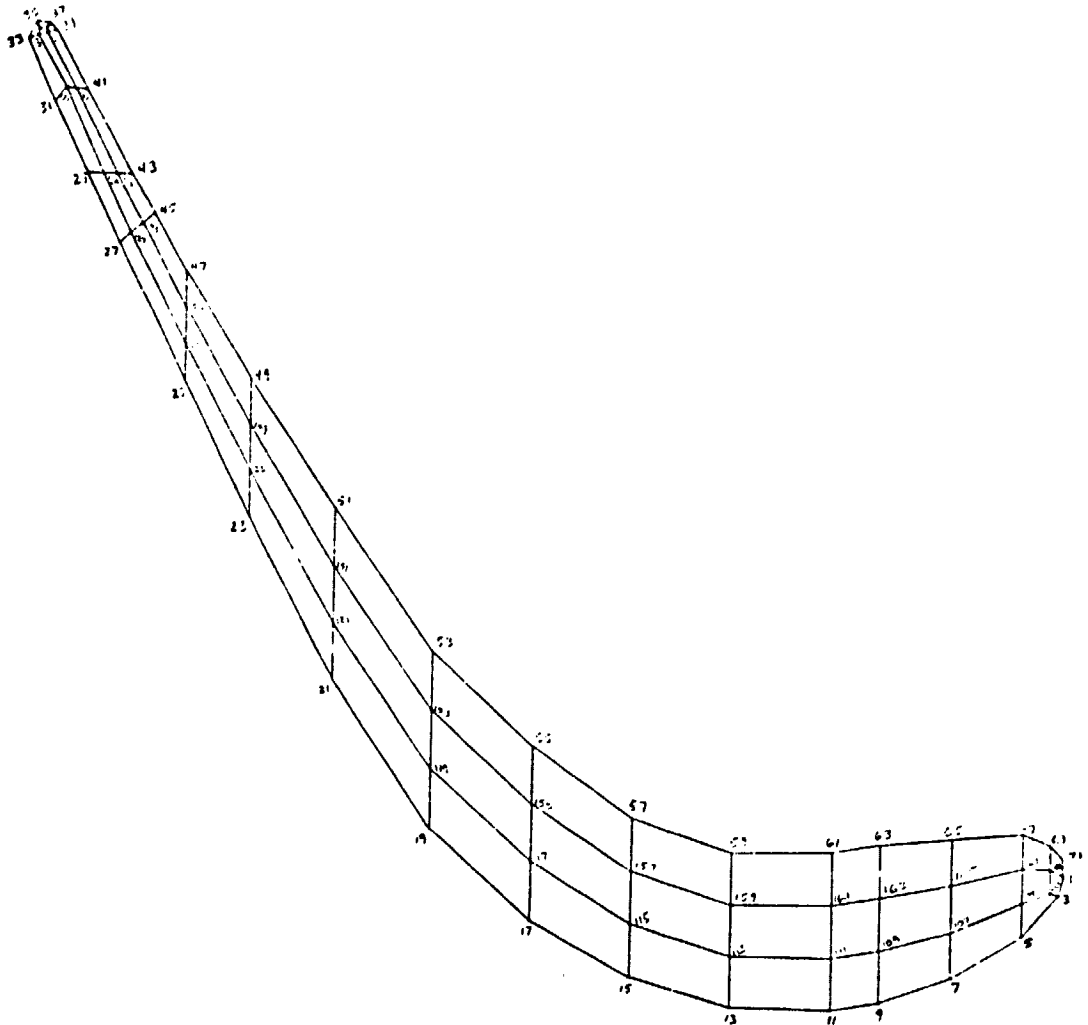


Fig. 2-2e F-2 Airfoil/Shank Grid Layout

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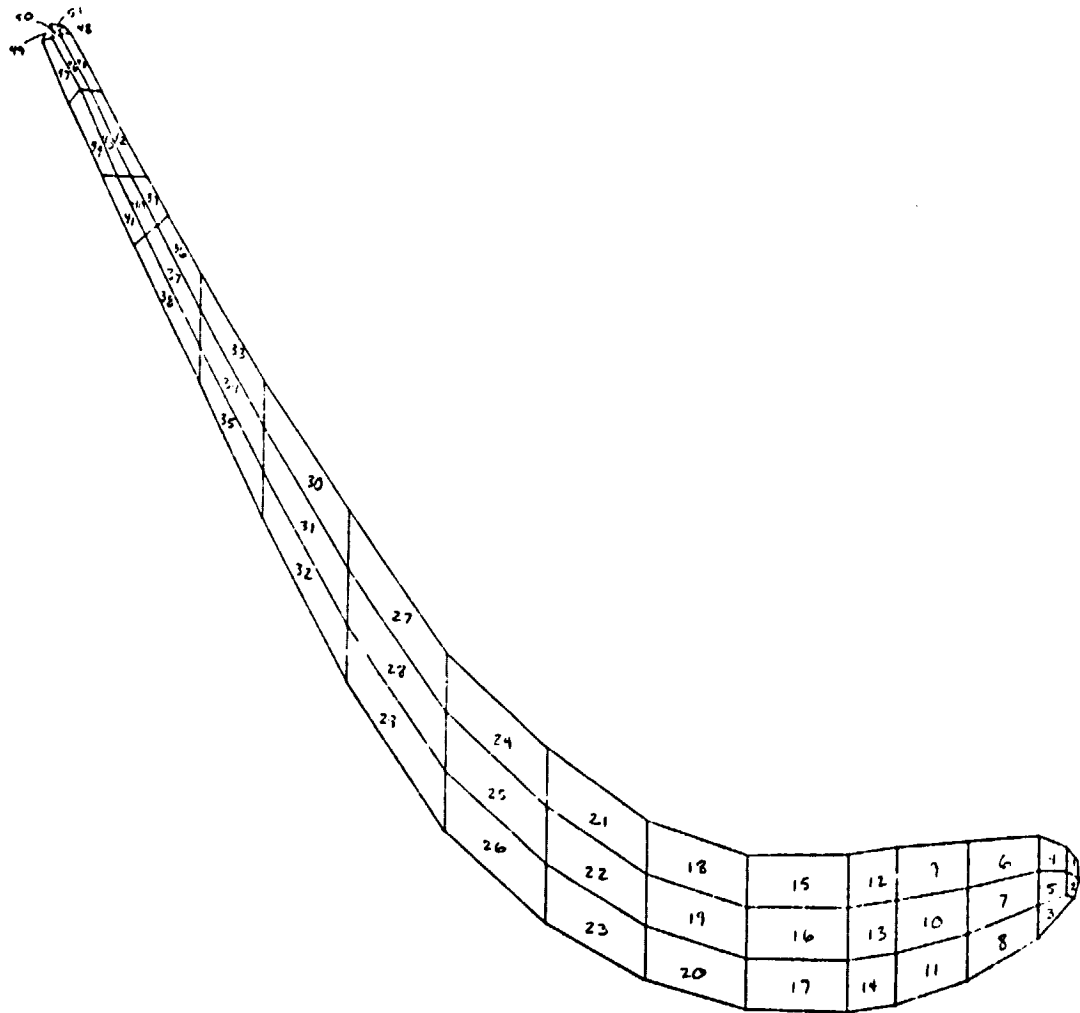


Fig. 2-2f F-2 Airfoil/Shank Element Layout

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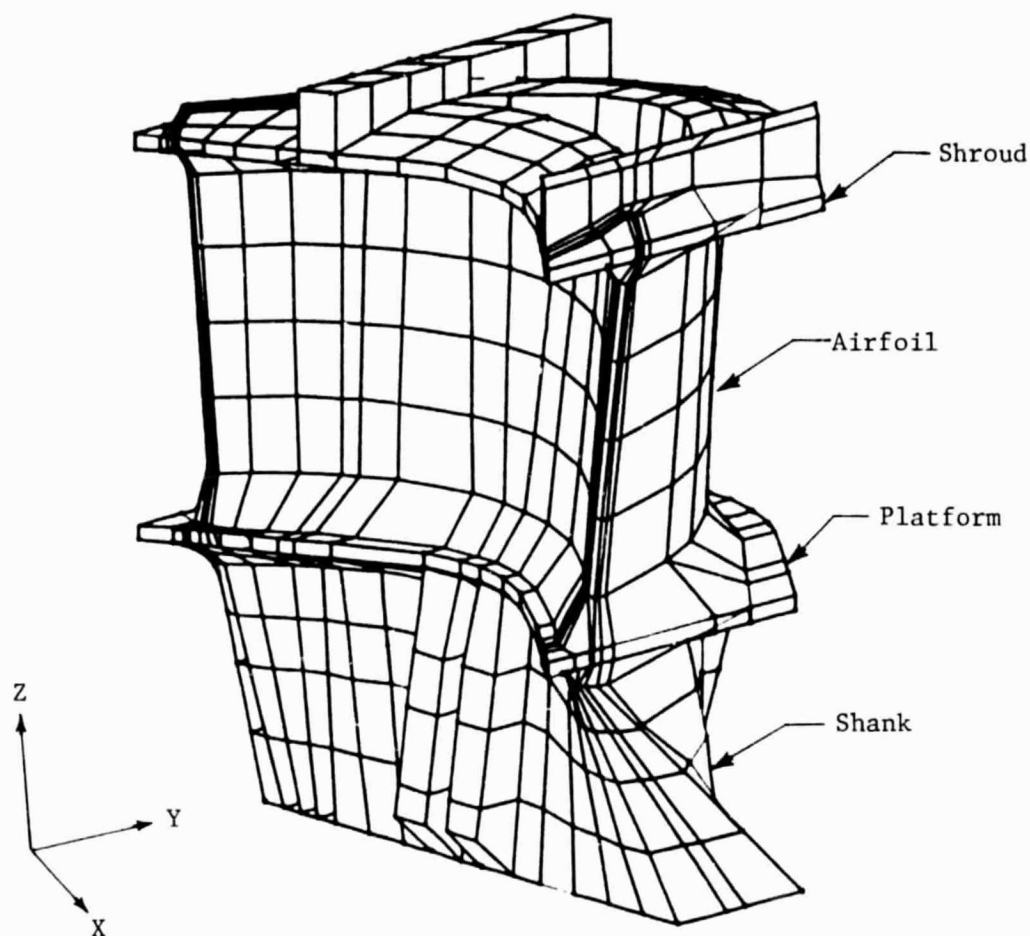


Fig. 2-3a HPOTP First Stage Turbine Blade (0-1) NASTRAN
Model (1137 Nodes, 618 Elements)

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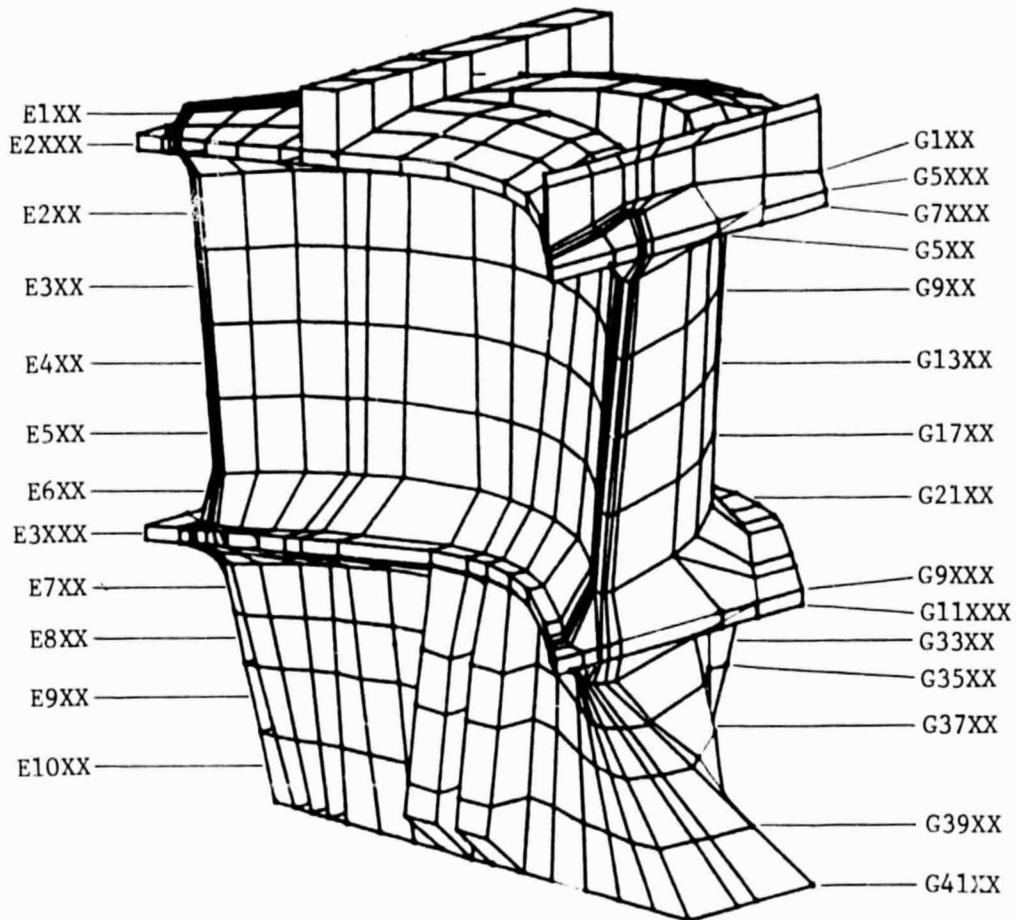


Fig. 2-3b 0-1 Element and Grid Prefixes

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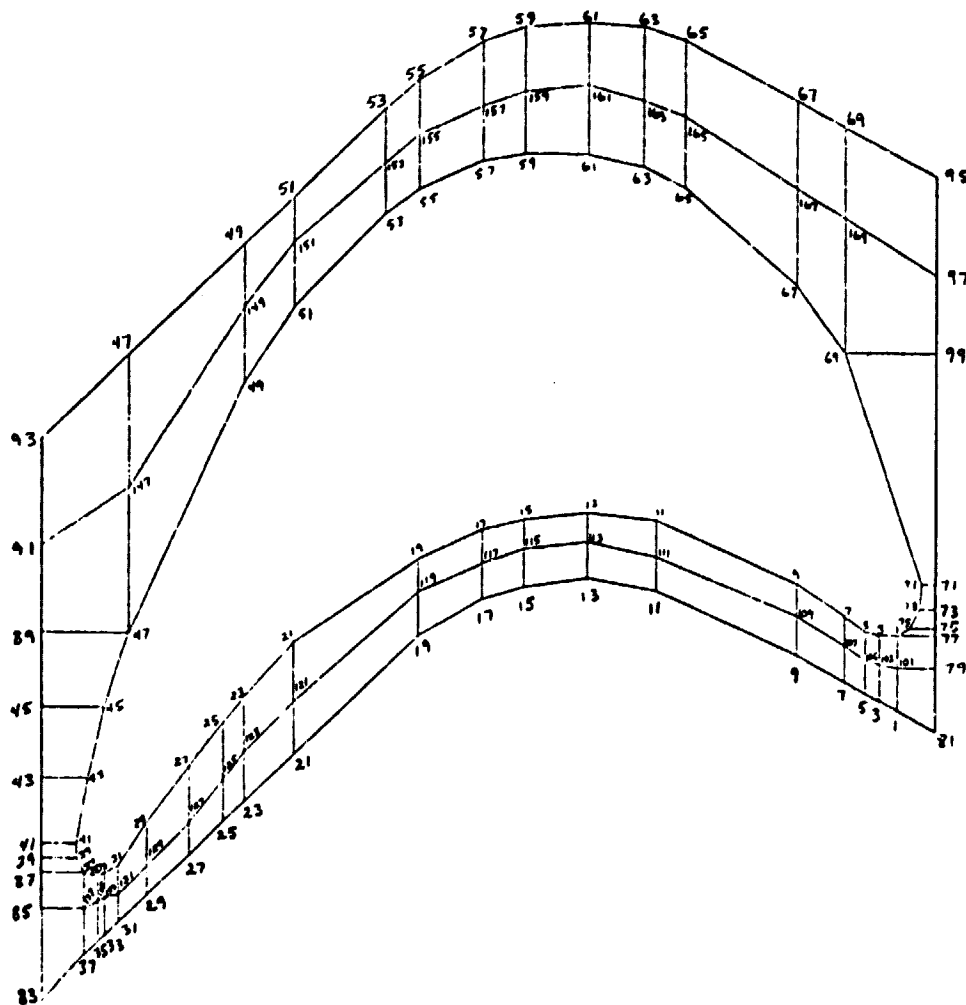


Fig. 2-3c 0-1 Shroud/Platform Grid Layout

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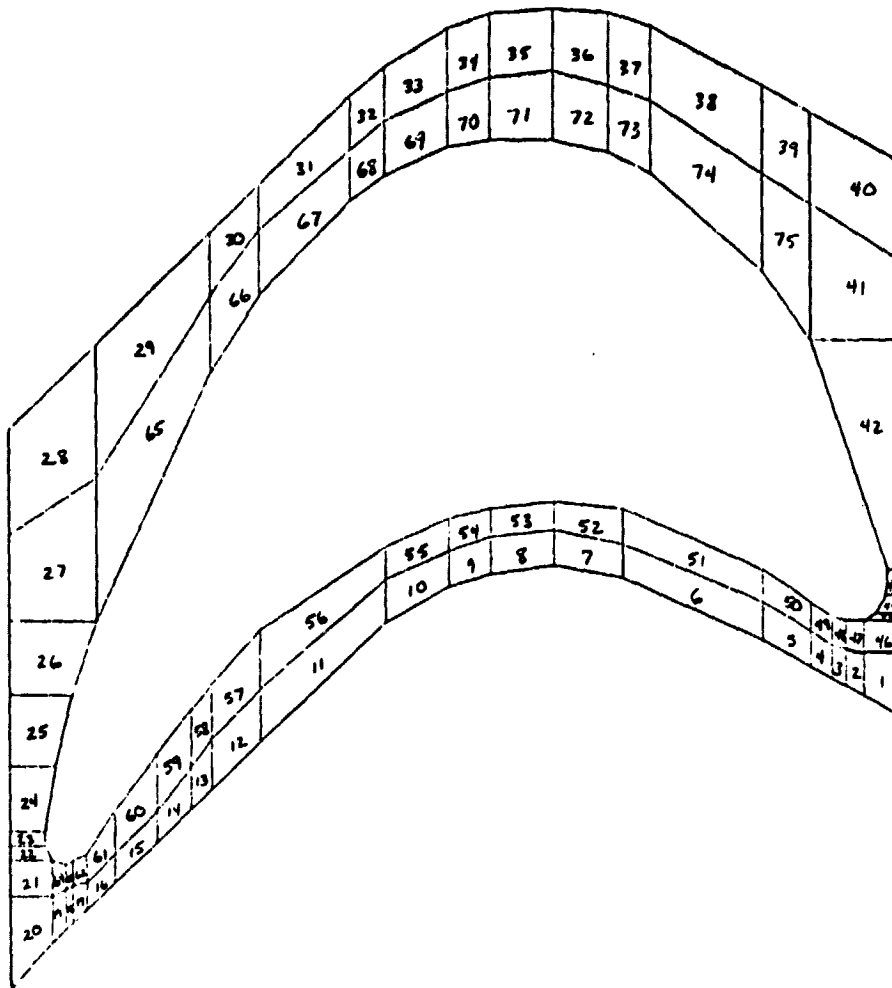


Fig. 2-3d 0-1 Shroud Platform/Element Layout

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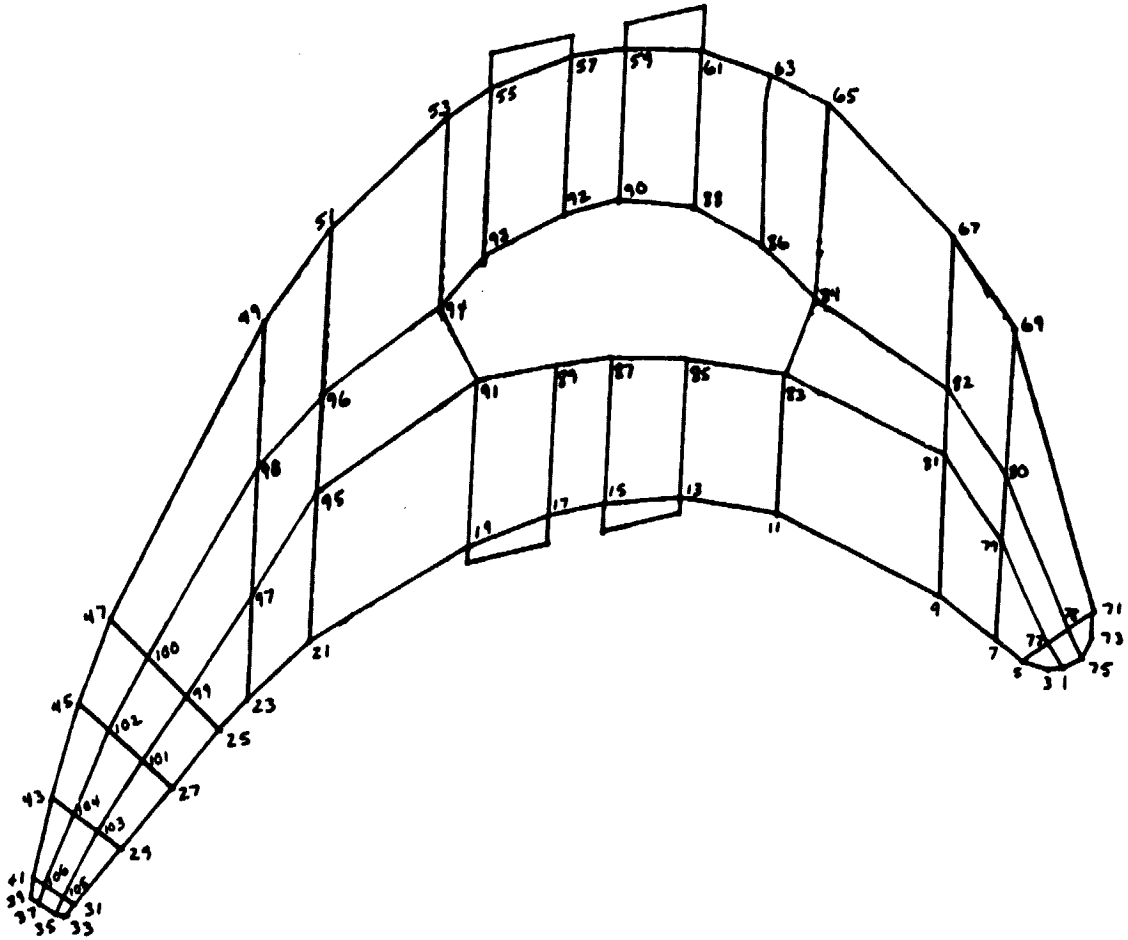


Fig. 2-3e 0-1 Airfoil/Shank Grid Layout

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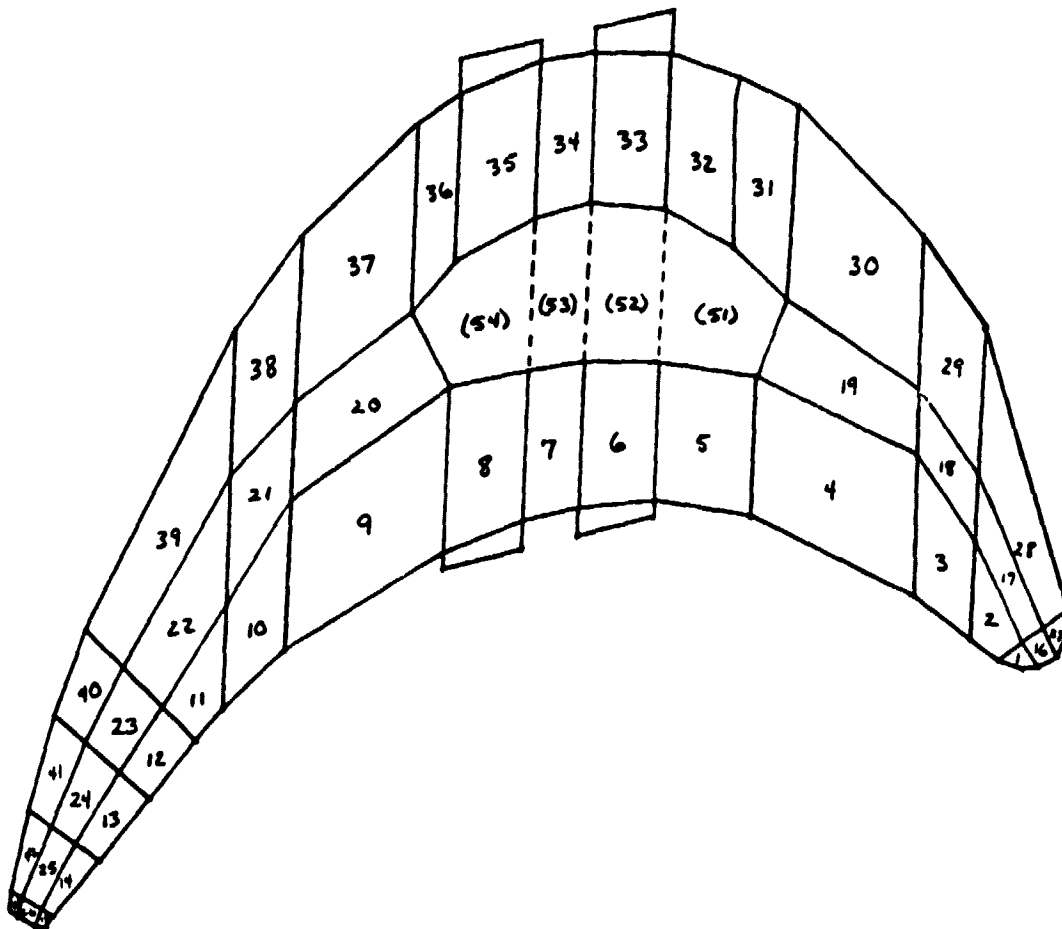


Fig. 2-3f 0-1 Airfoil/Shank Element Layout

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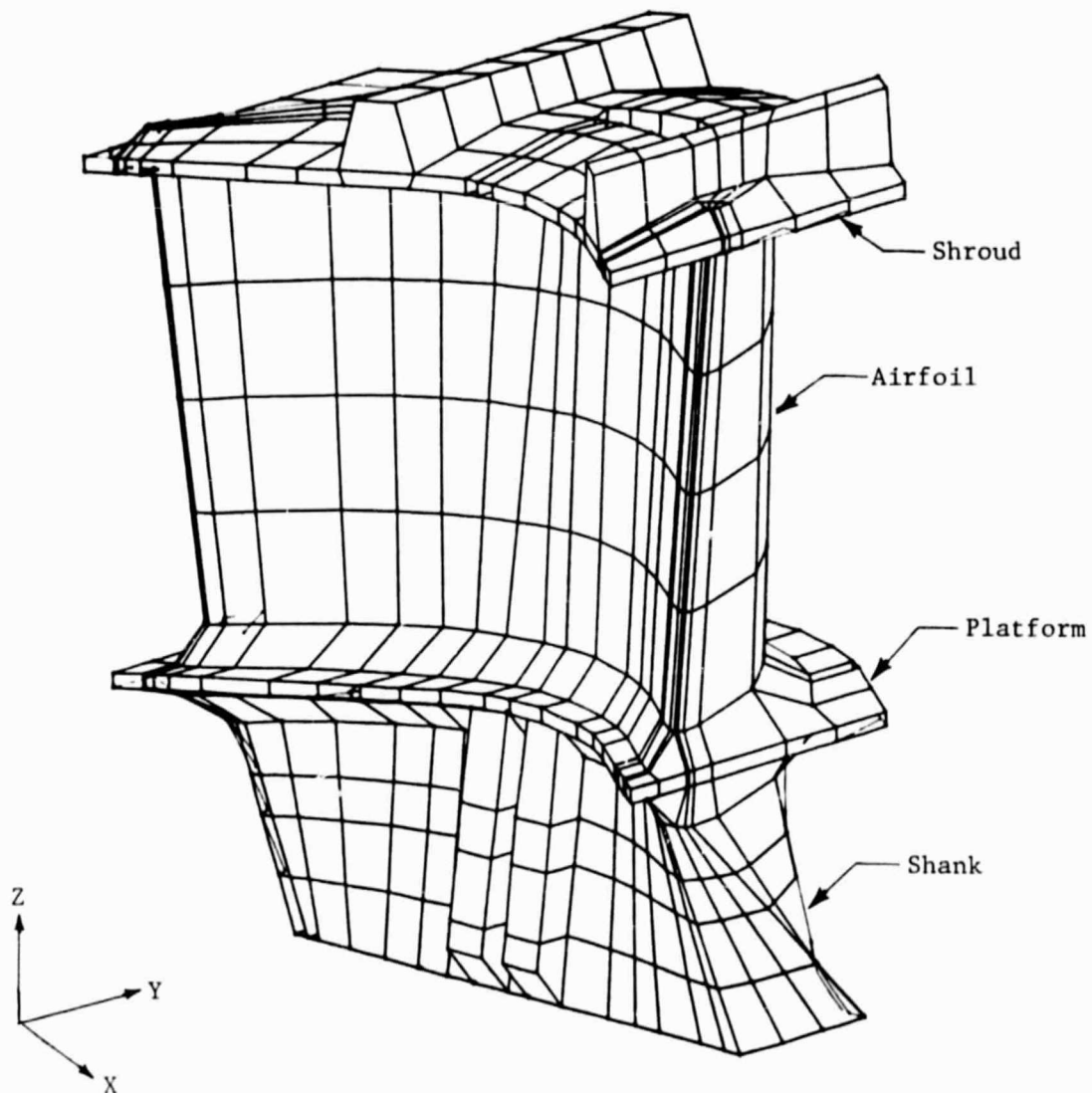


Fig. 2-4a HPOTP Stage Turbine Blade (0-2) NASTRAN Model
(1140 Nodes, 622 Elements)

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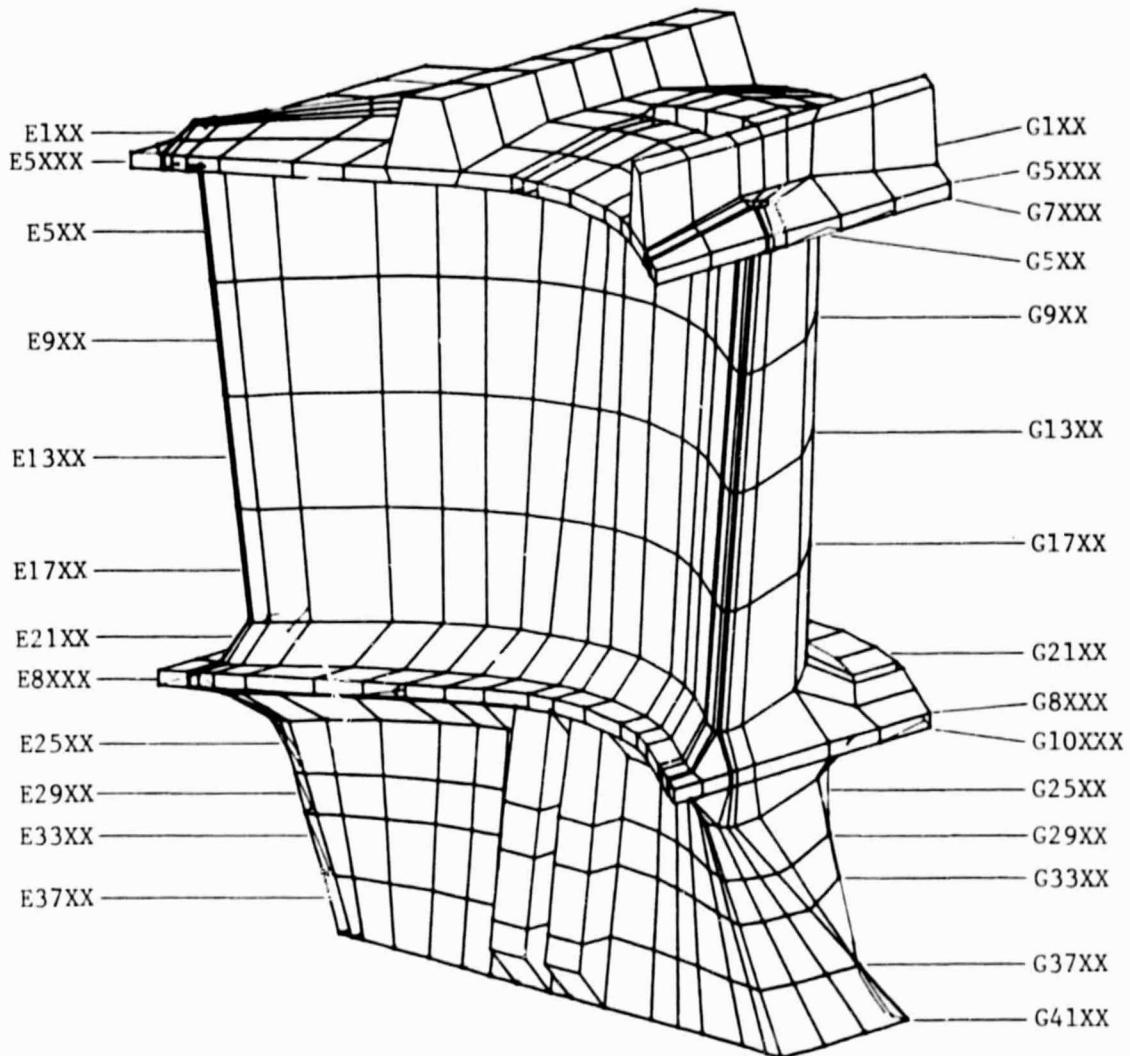
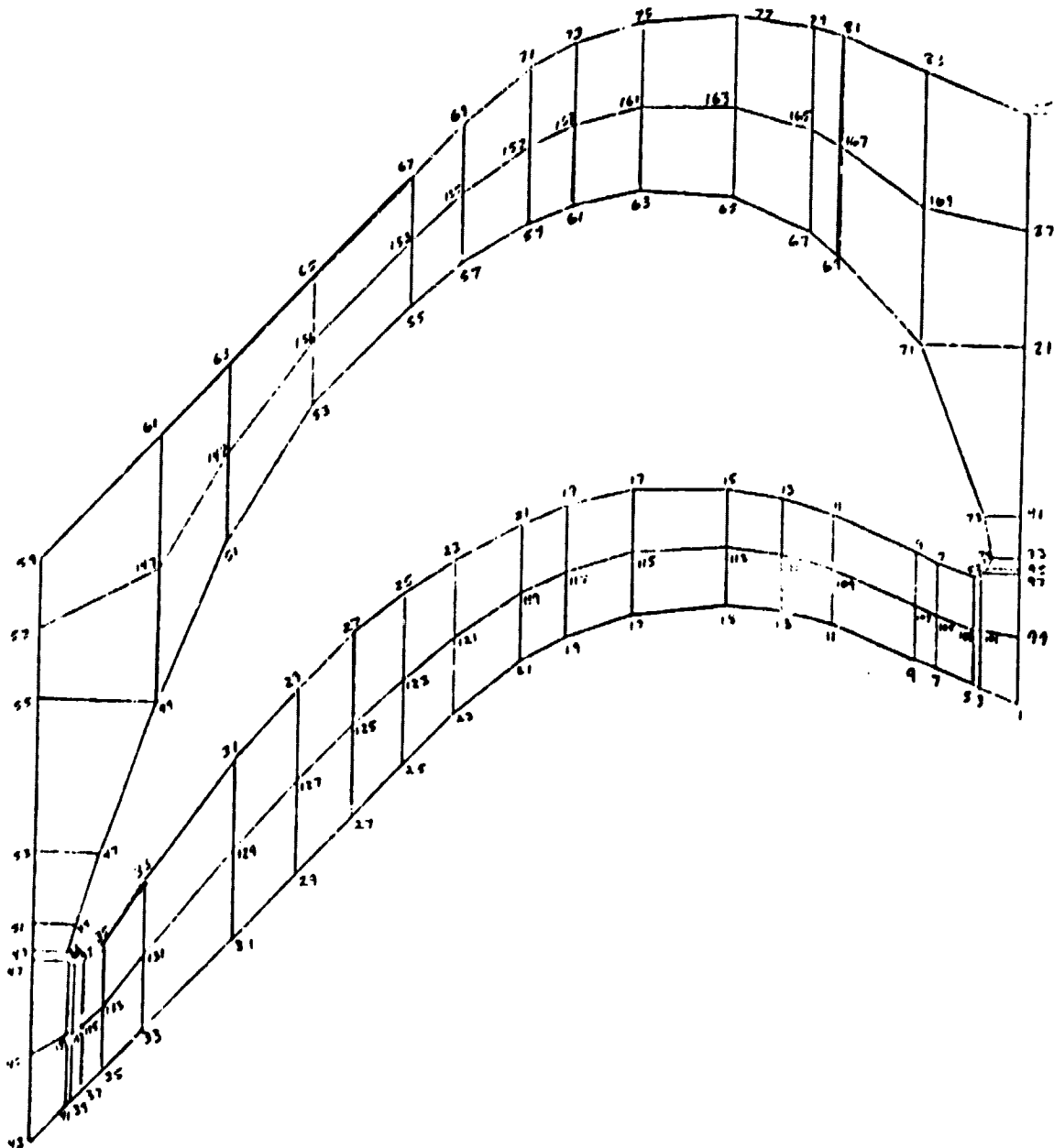


Fig. 2-4b 0-2 Element and Grid Prefixes



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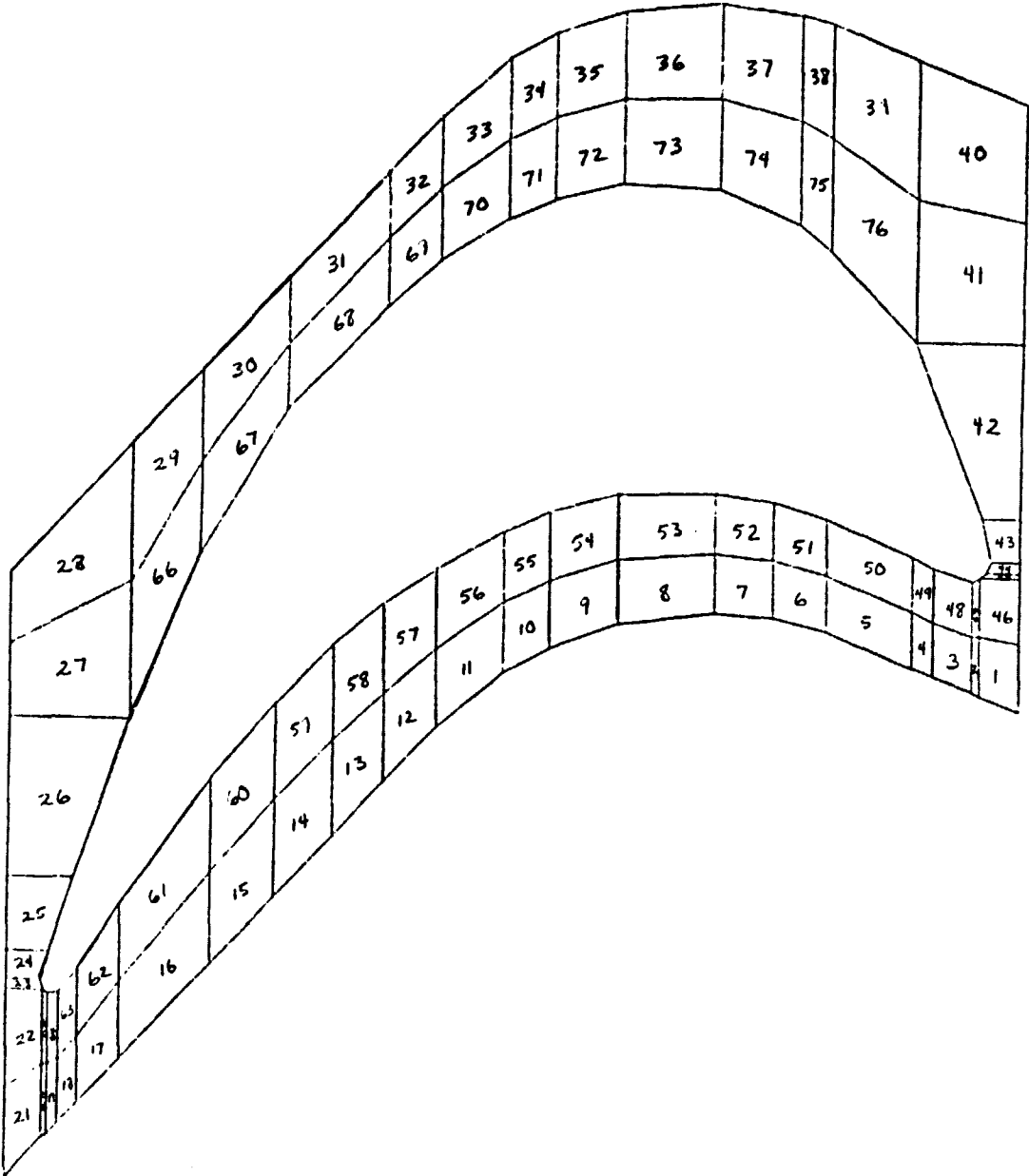
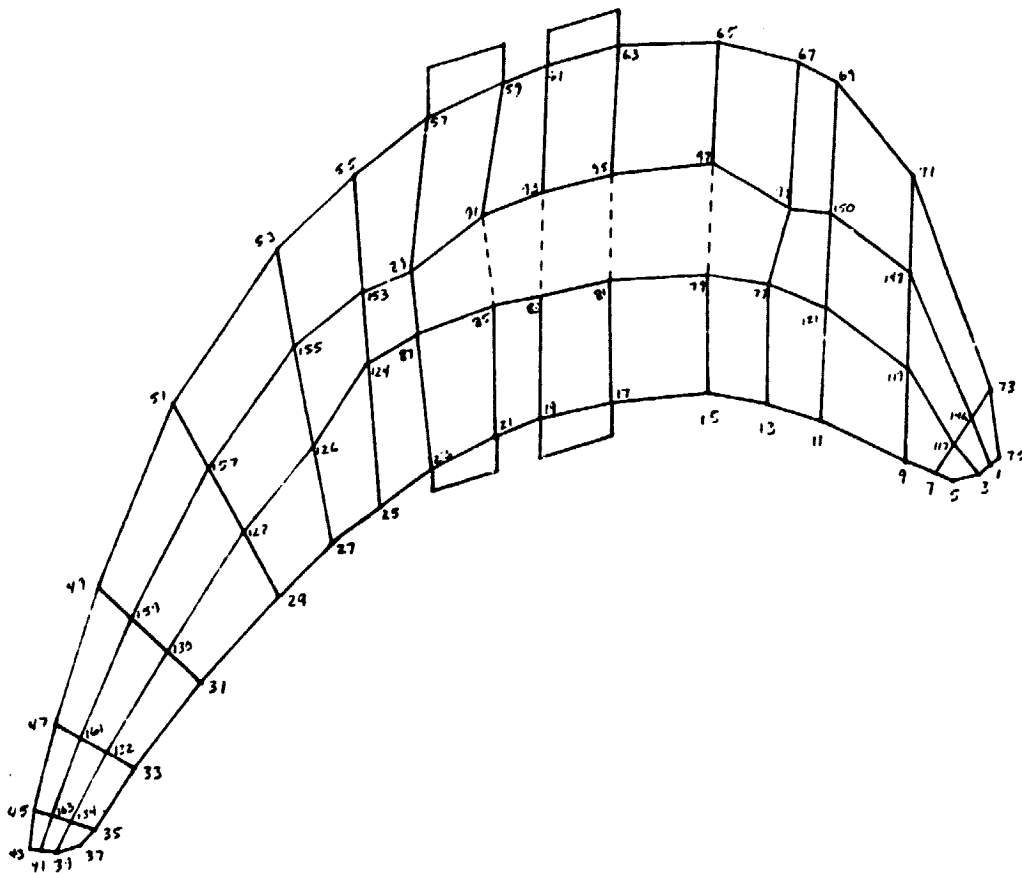


Fig. 2-4d 0-2 Shroud/Platform Element Layout

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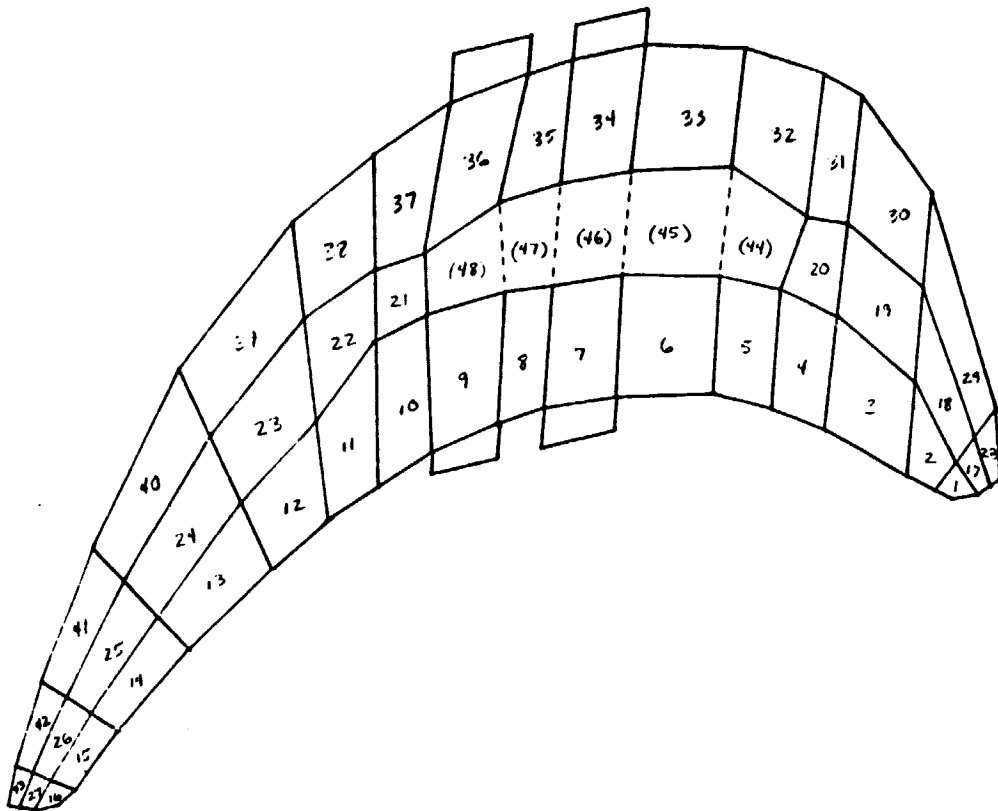


Fig. 2-4f 0-2 Airfoil/Shank Element Layout

2.2 HPFTP FIRST STAGE TURBINE BLADE DYNAMICS

The first 10 normal modes are summarized in Table 2-1 and Figs. 2-5 through 2-14. The Campbell diagram is shown in Fig. 2-15.

Table 2-1
HPFTP FIRST STAGE TURBINE BLADE NORMAL MODES

<u>Mode</u>	<u>Frequency (Hz)</u>
1	4642
2	8239
3	12186
4	15959
5	19002
6	21469
7	23099
8	27832
9	31961
10	33210

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Fig. 2-5 Model F-1, Mode 1, Freq 4642

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Fig. 2-6 Model F-1, Mode 2, Freq 8239

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Fig. 2-7 Model F-1, Mode 3, Freq 12186

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Fig. 2-8 Model F-1, Mode 4, Freq 15959

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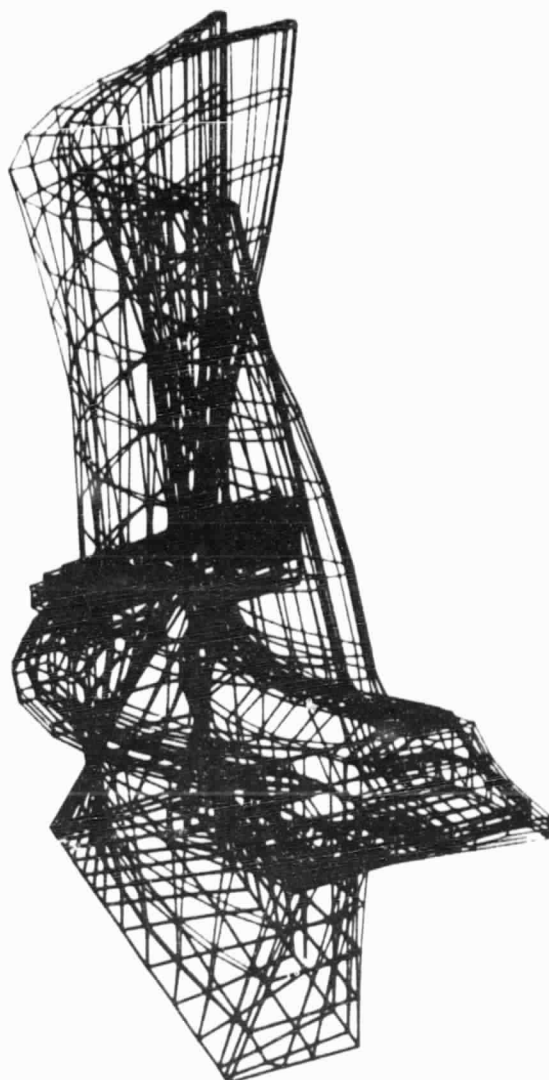


Fig. 2-9 Model F-1, Mode 5, Freq 19002

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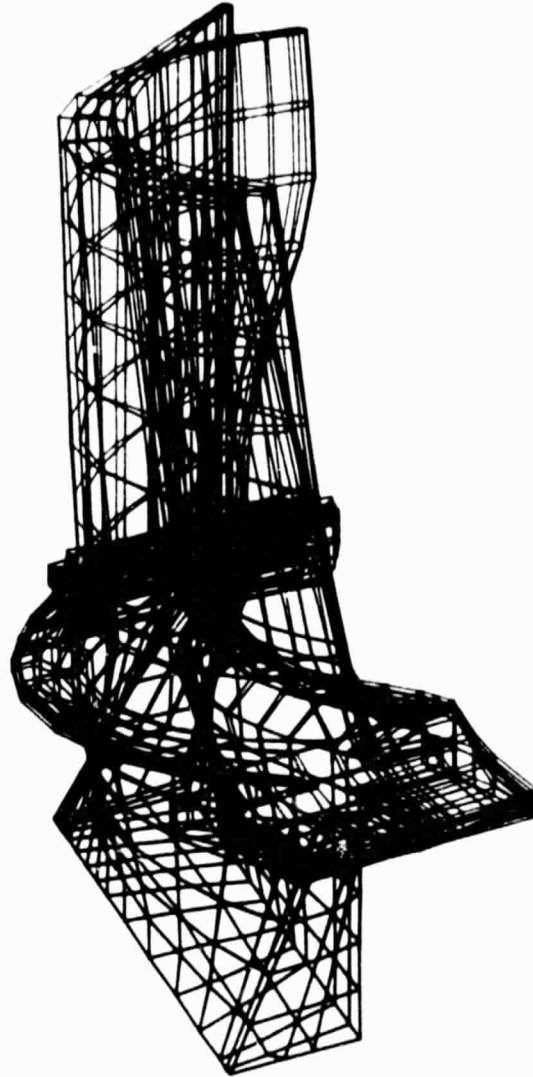


Fig. 2-10 Model F-1, Mode 6, Freq 21469

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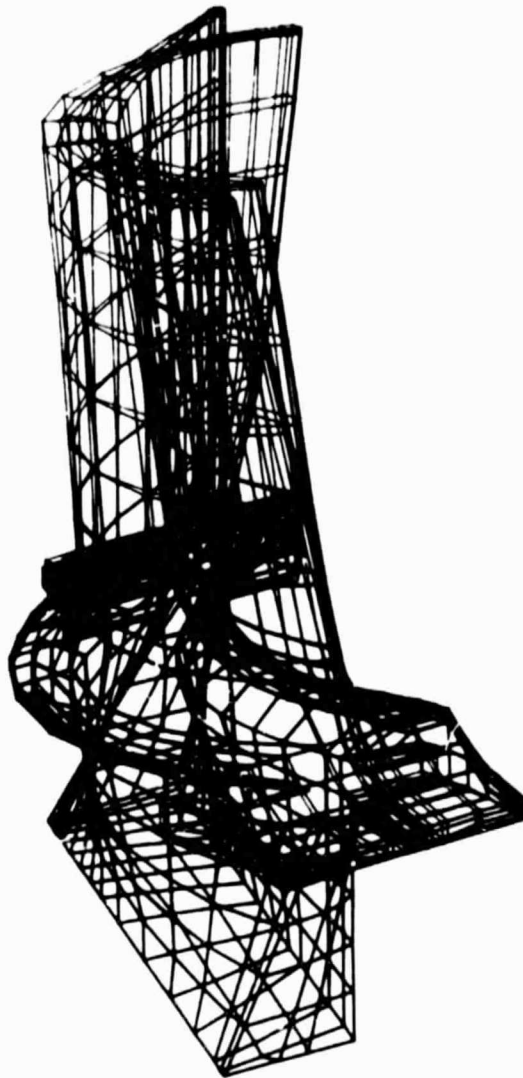


Fig. 2-11 Model F-1, Mode 7, Freq 23099

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Fig. 2-12 Model F-1, Mode 8, Freq 27832

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Fig. 2-13 Model F-1, Mode 9, Freq 31961

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Fig. 2-14 Model F-1, Mode 10, Freq 33210

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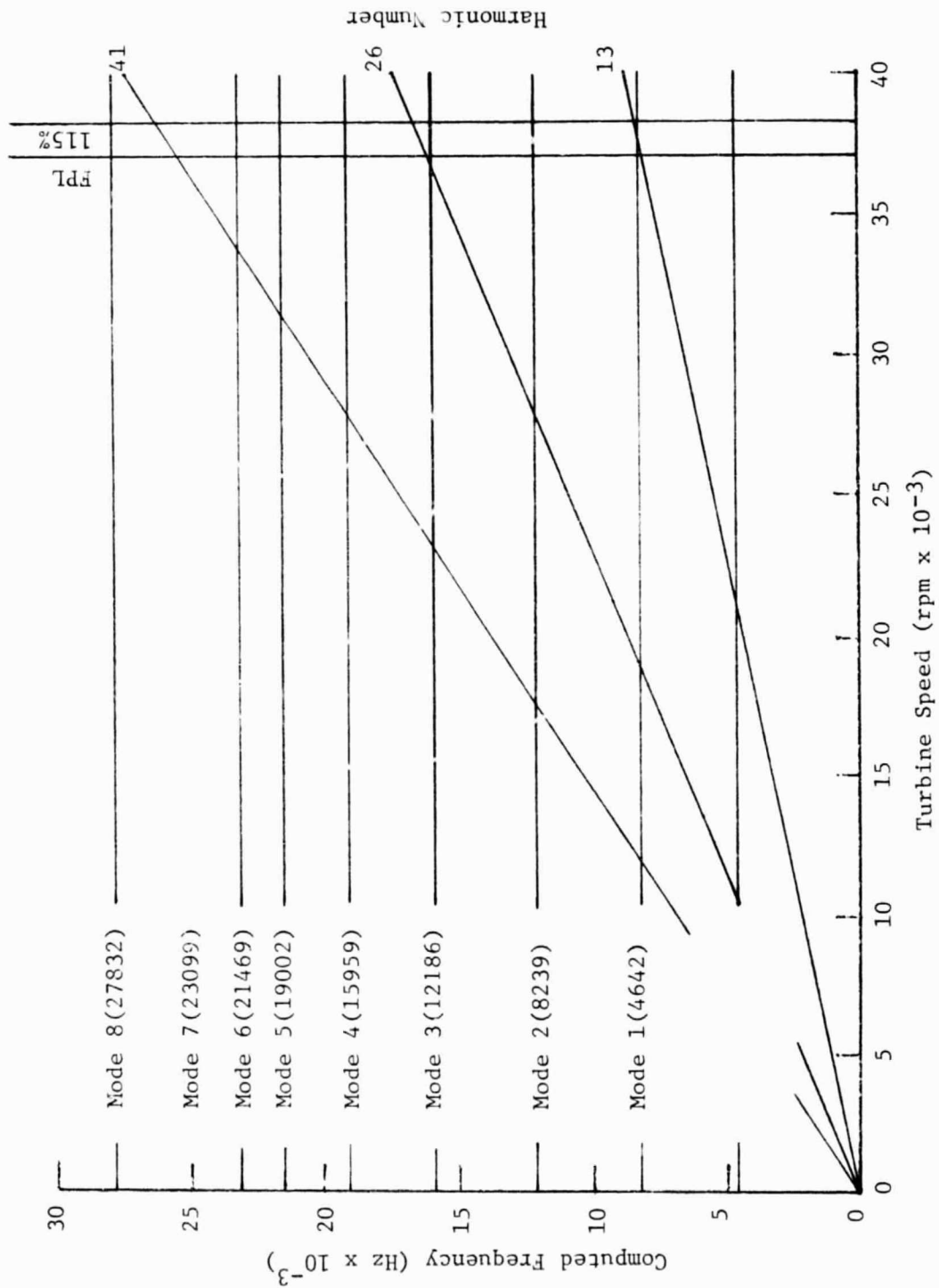


Fig. 2-15 HPFTP First Stage Turbine Blade Campbell Diagram

2.3 HPFTP SECOND STAGE TURBINE BLADE DYNAMICS

The first ten normal modes are summarized in Table 2-2 and Figs. 2-16 through 2-25. The Campbell diagram is shown in Fig. 2-26

Table 2-2
HPFTP FIRST STAGE TURBINE BLADE NORMAL MODES

<u>Mode</u>	<u>Frequency (Hz)</u>
1	4495
2	7815
3	11670
4	16625
5	19189
6	24720
7	29160
8	29760
9	32209
10	32773

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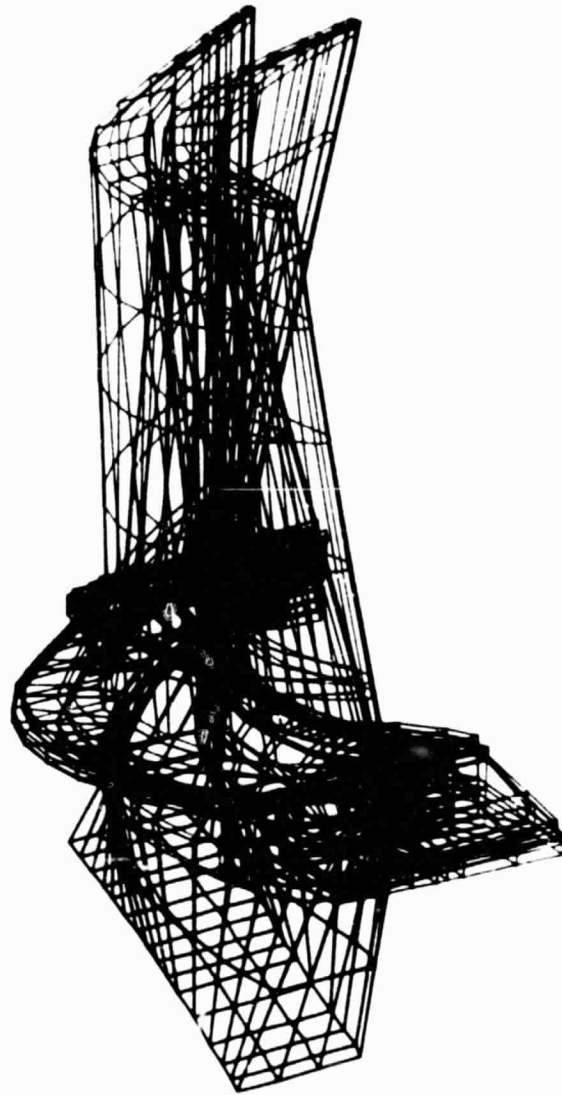


Fig. 2-16 Model F-2, Mode 1, Freq 4495

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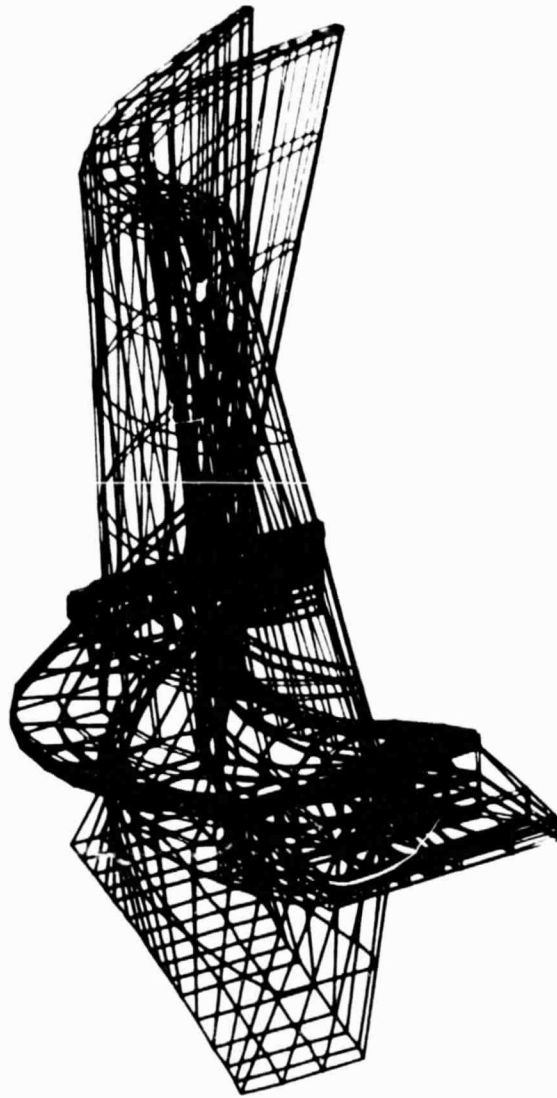


Fig. 2-17 Model F-2, Mode 2, Freq 7815

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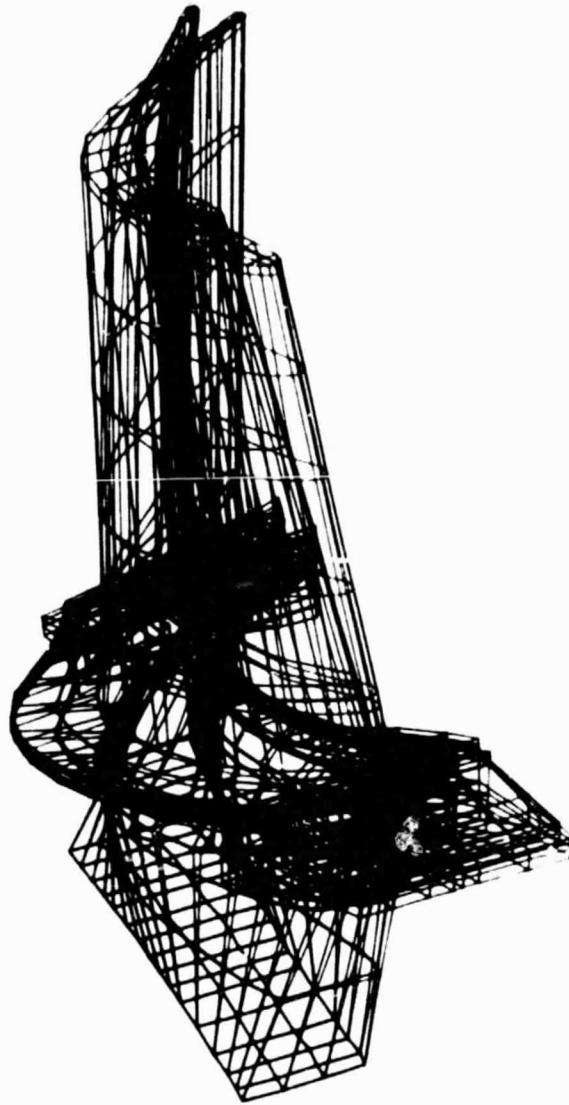


Fig. 2-18 Model F-2, Mode 3, Freq 11670

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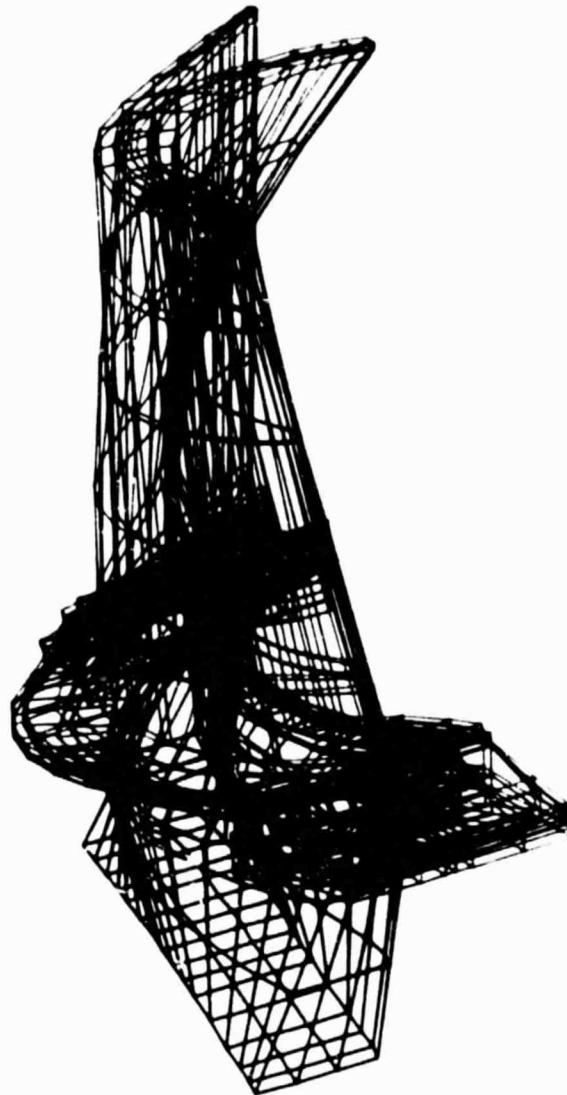


Fig. 2-19 Model F-2, Mode 4, Freq 16625

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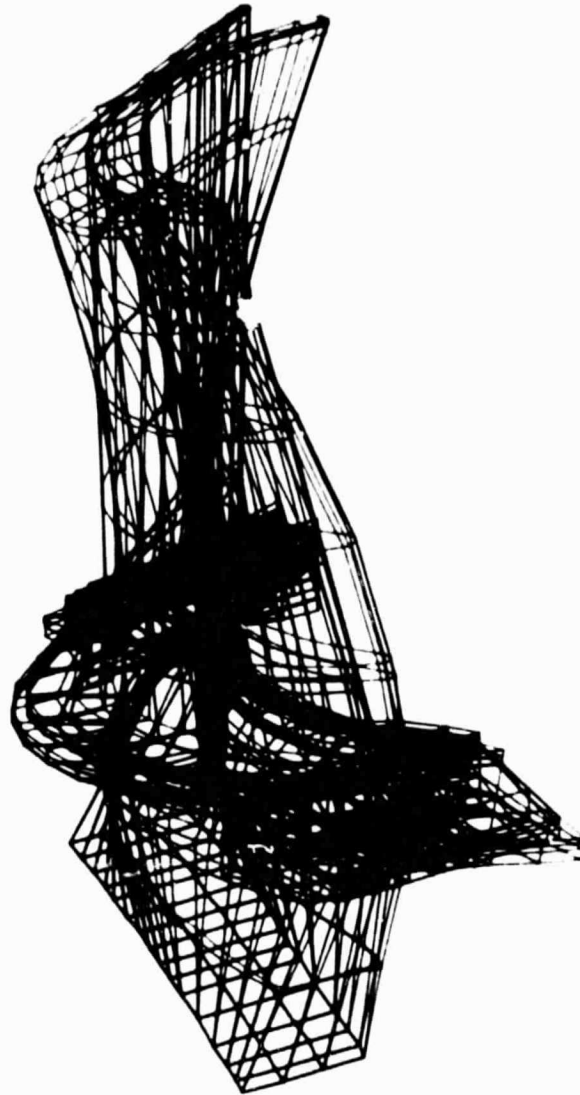


Fig. 2-20 Model F-2, Mode 5, Freq 19189

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Fig. 2-21 Model F-2, Mode 6, Freq 24720

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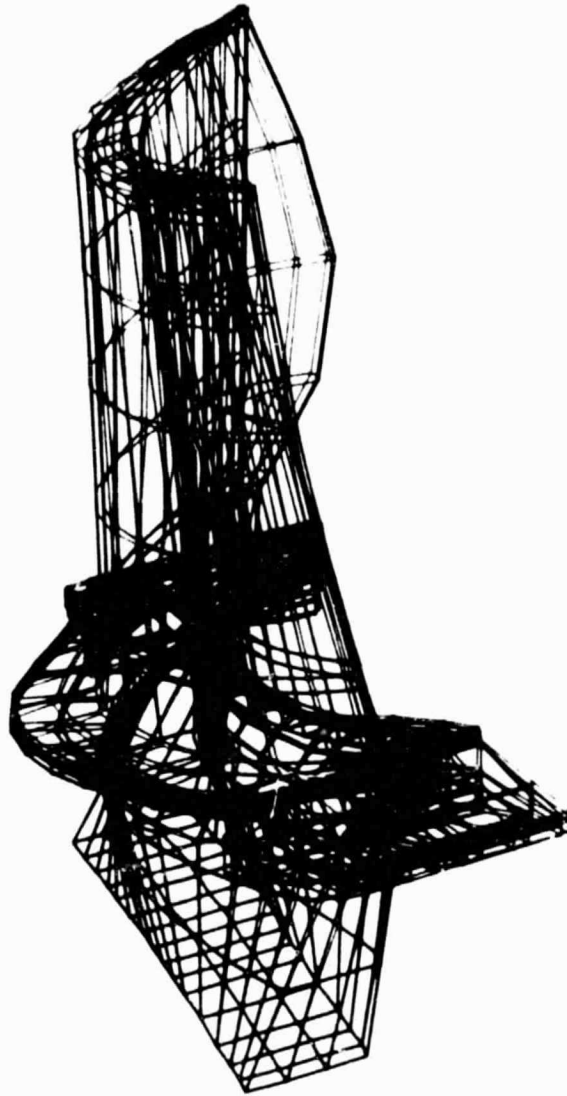


Fig. 2-22 Model F-2, Mode 7, Freq 29160

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Fig. 2-23 Model F-2, Mode 8, Freq 29760

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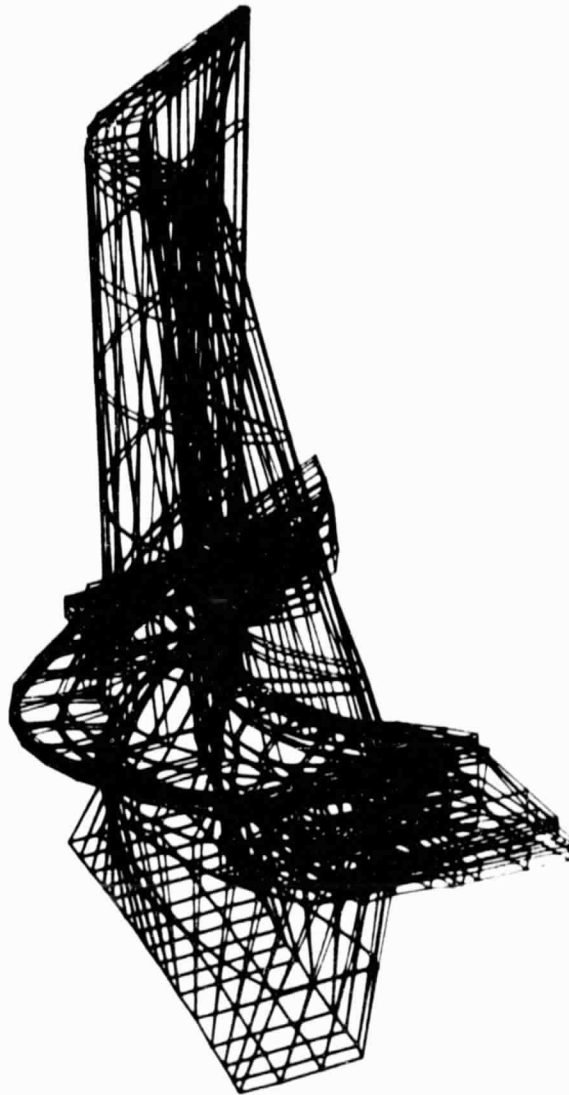


Fig. 2-24 Model F-2, Mode 9, Freq 32209

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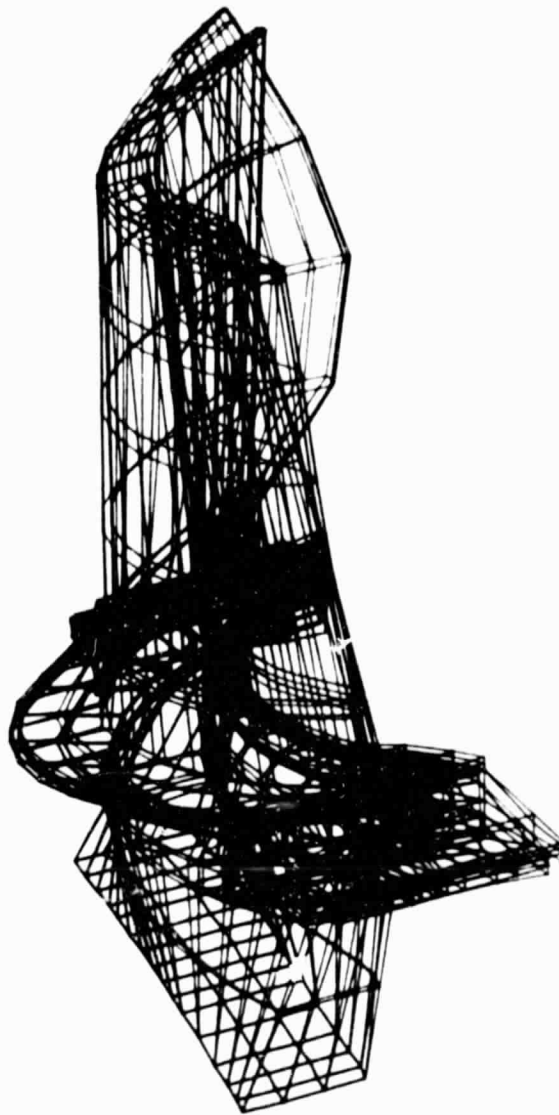


Fig. 2-25 Model F-2, Mode 10, Freq 32773

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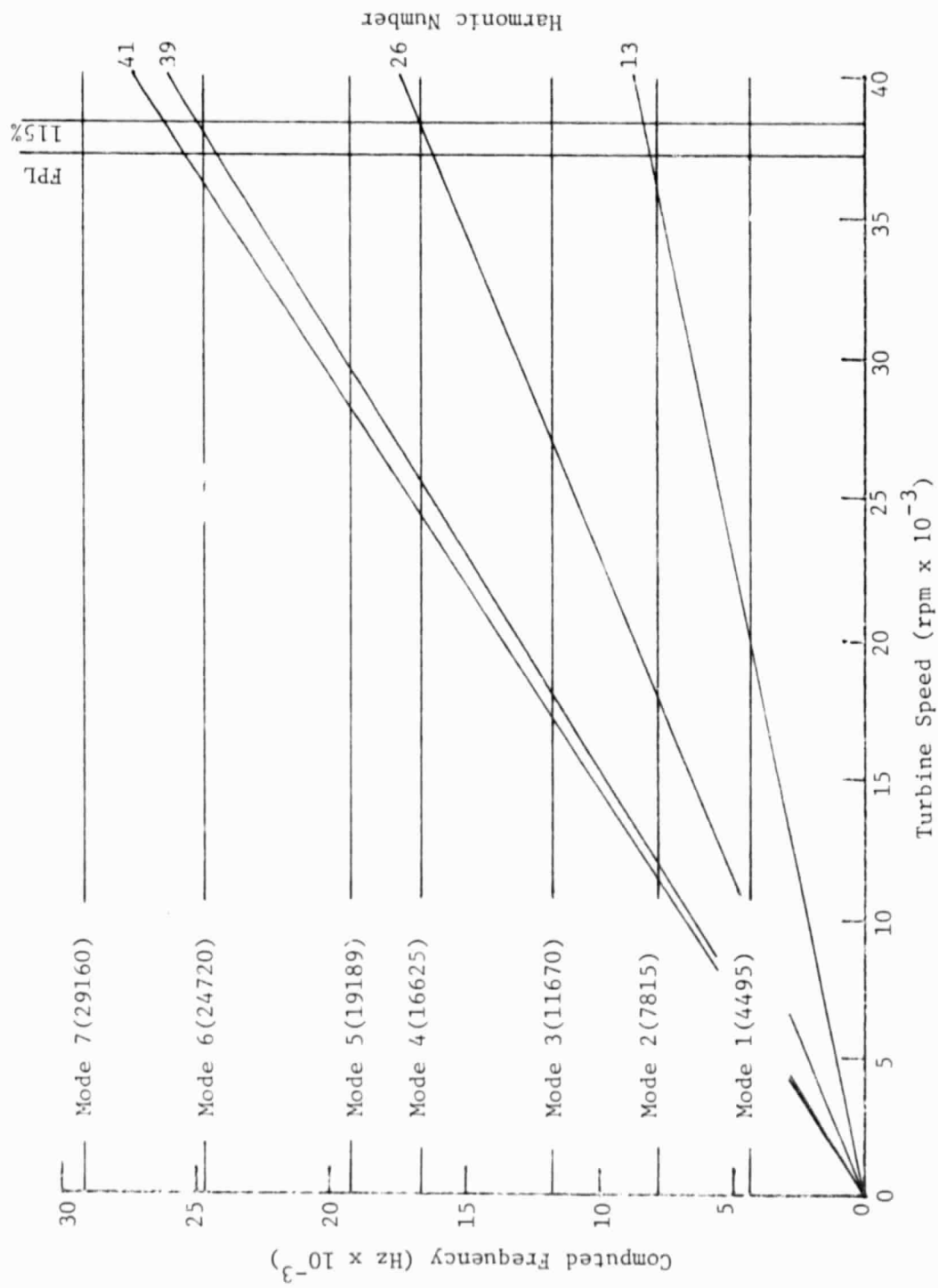


Fig. 2-26 HPFTP Second Stage Turbine Blade Campbell Diagram

2.4 HPOTP FIRST STAGE TURBINE BLADE DYNAMICS

The first ten normal modes are summarized in Table 2-3 and Figs. 2-27 through 2-37.

Table 2-3
HPOTP FIRST STAGE TURBINE BLADE NORMAL MODES

<u>Mode</u>	<u>Frequency (Hz)</u>
1	6626
2	12335
3	14848
4	29902
5	35521
6	41743
7	43037
8	51516
9	60815
10	62167

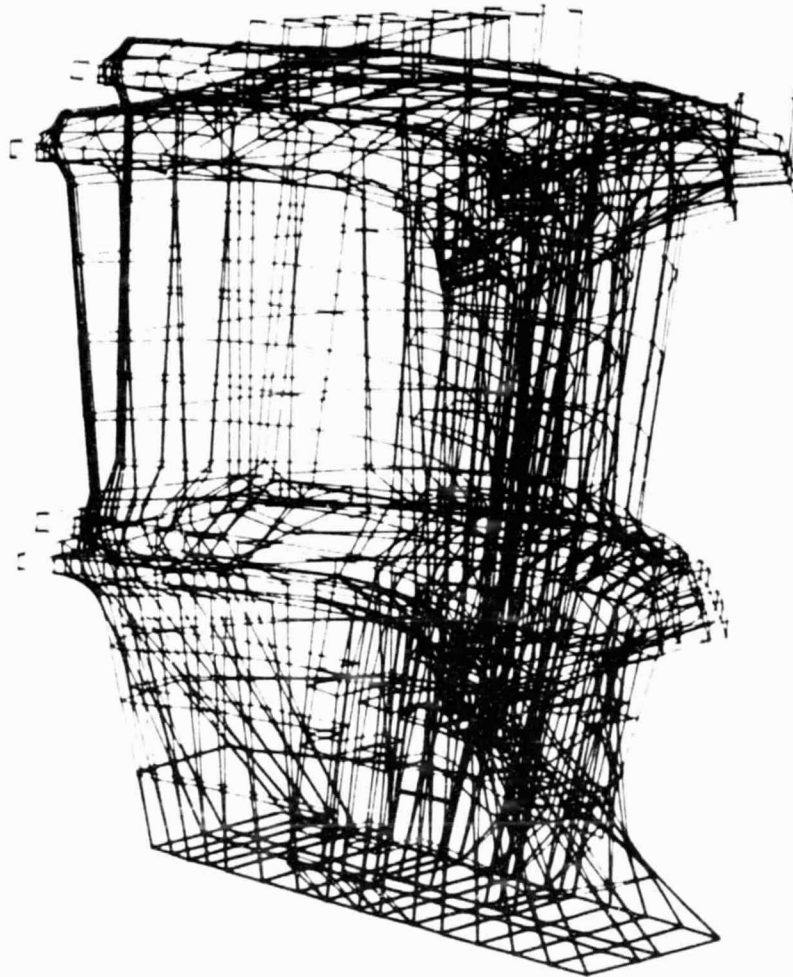


Fig. 2-27 Model O-1, Mode 1, Freq 6626

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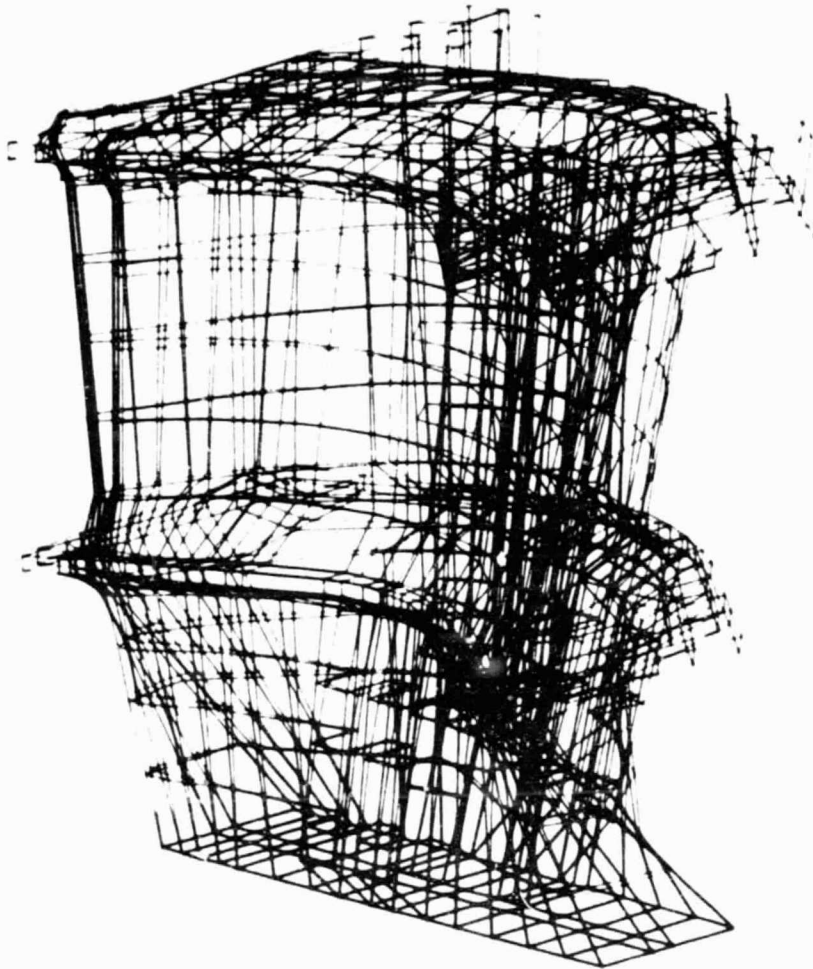


Fig. 2-28 Model O-1, Mode 2, Freq 12335

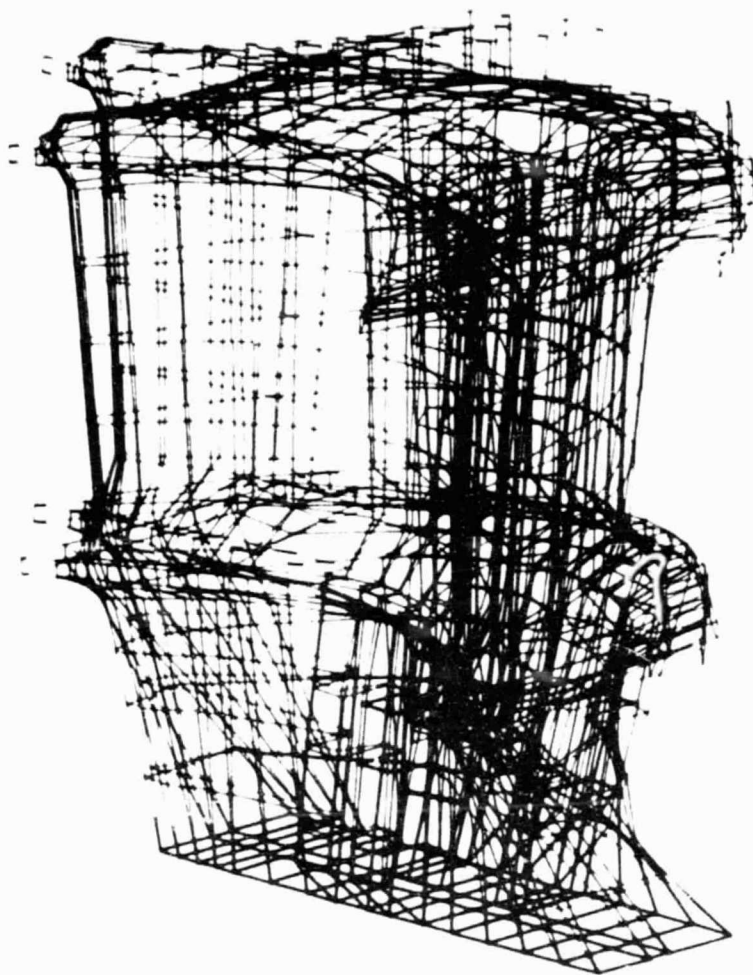


Fig. 2-29 Model 0-1, Mode 3, Freq 14848

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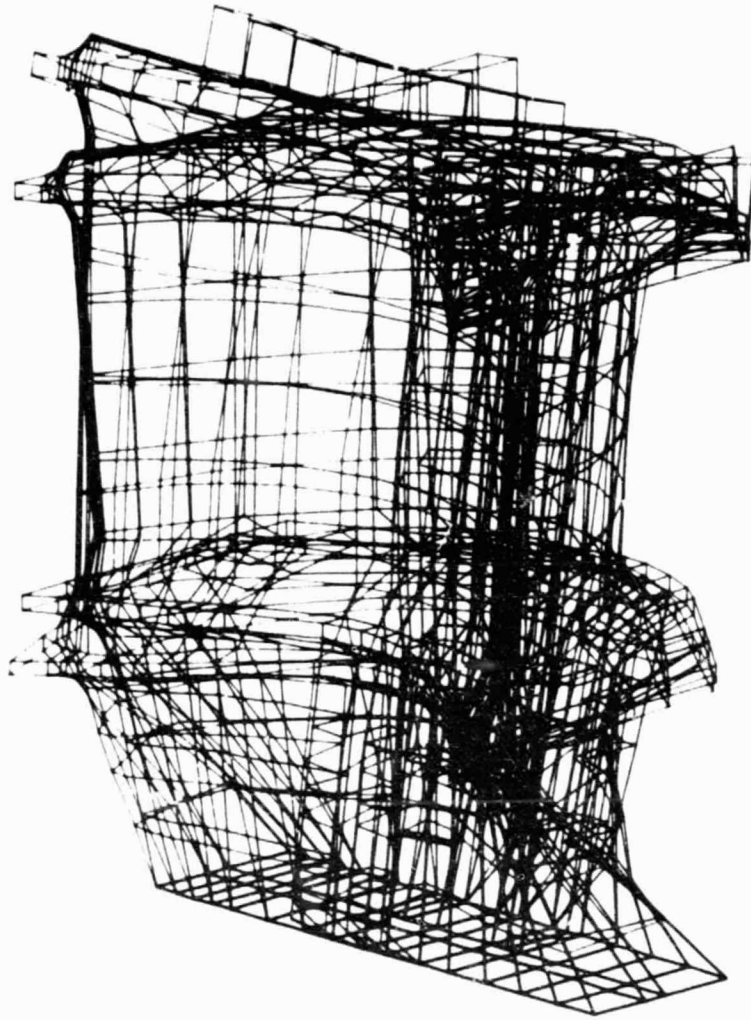


Fig. 2-30 Model 0-1, Mode 4, Freq 29902

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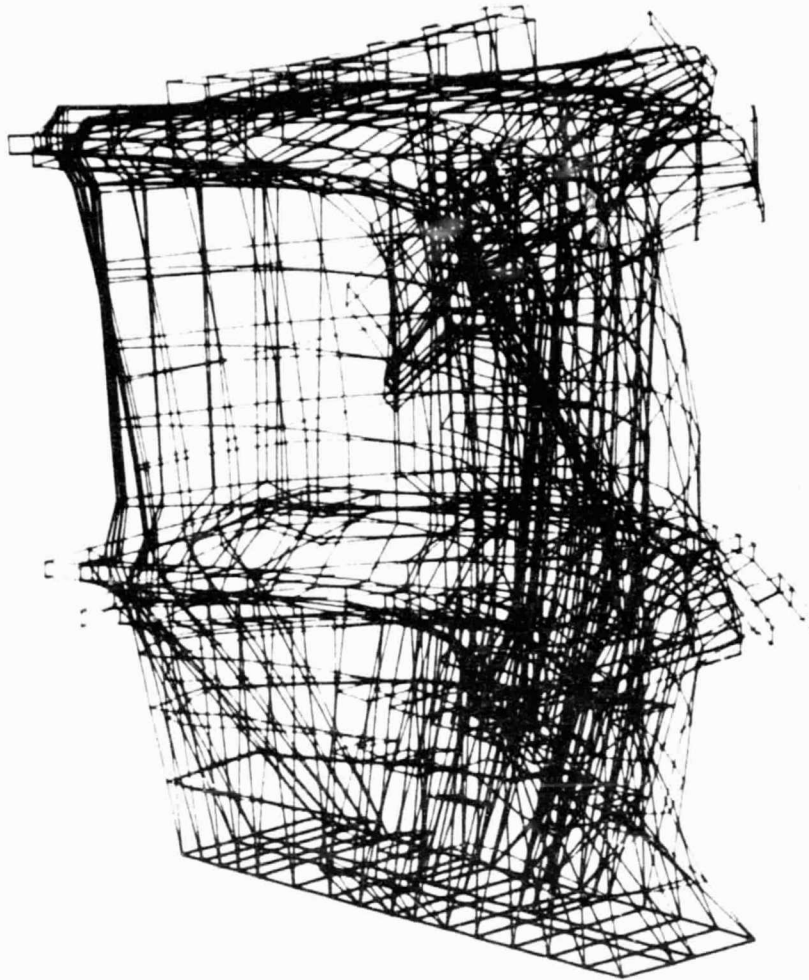


Fig. 2-31 Model 0-1, Mode 5, Freq 35521

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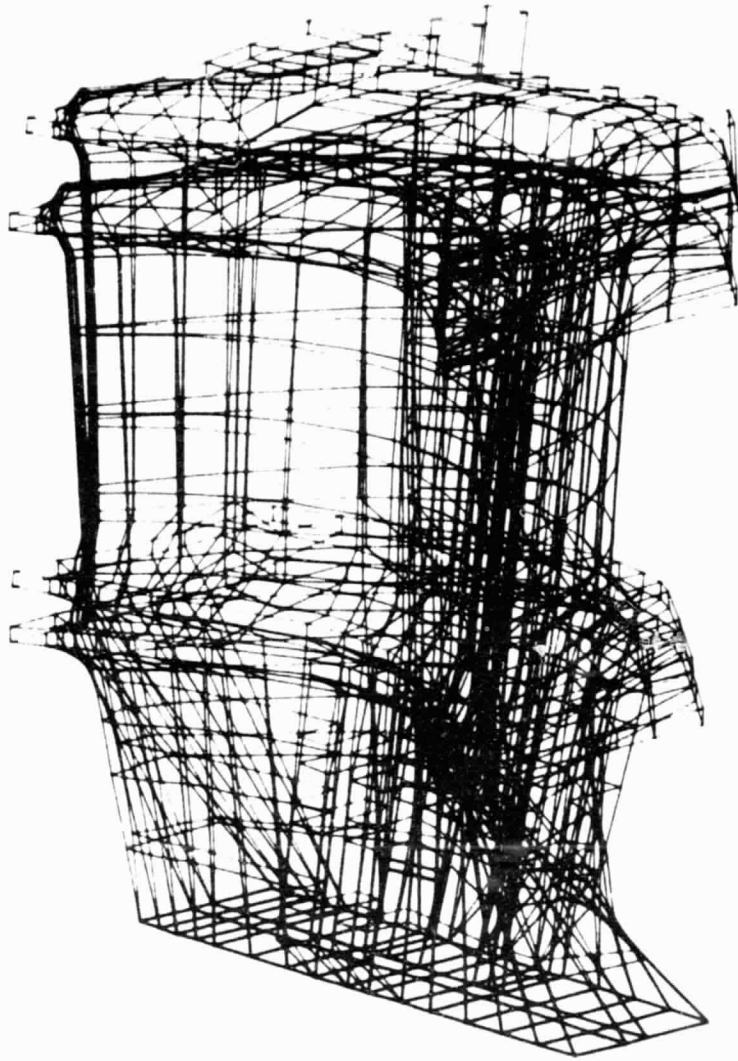


Fig. 2-32 Model 0-1, Mode 6, Freq 41743

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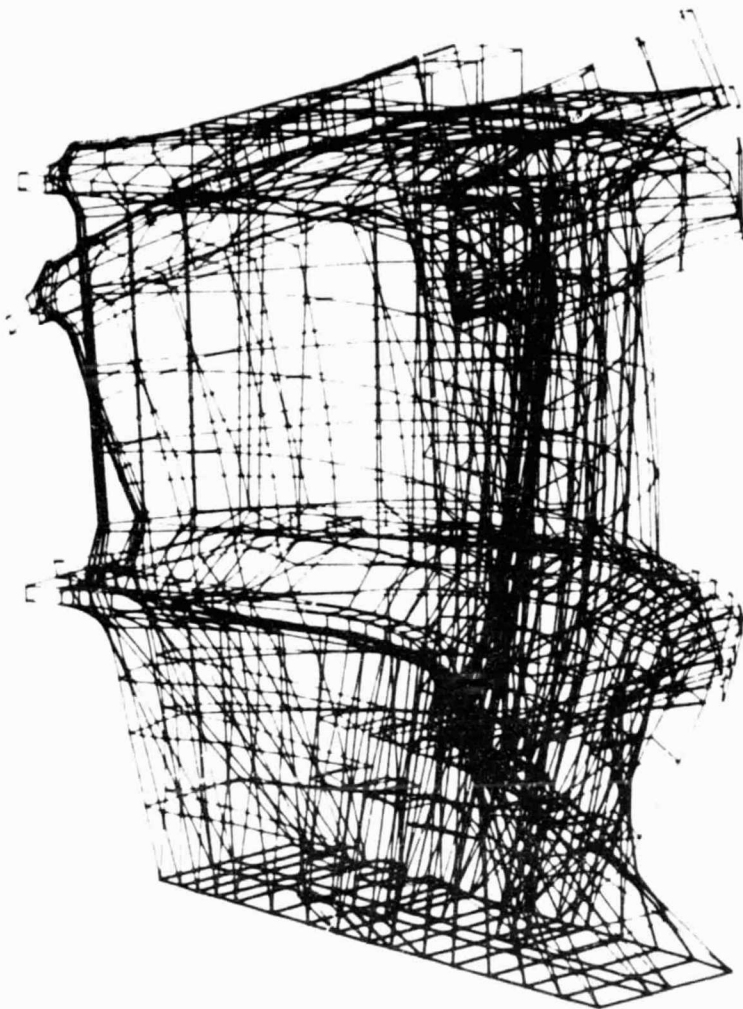


Fig. 2-33 Model 0-1, Mode 7, Freq 43037

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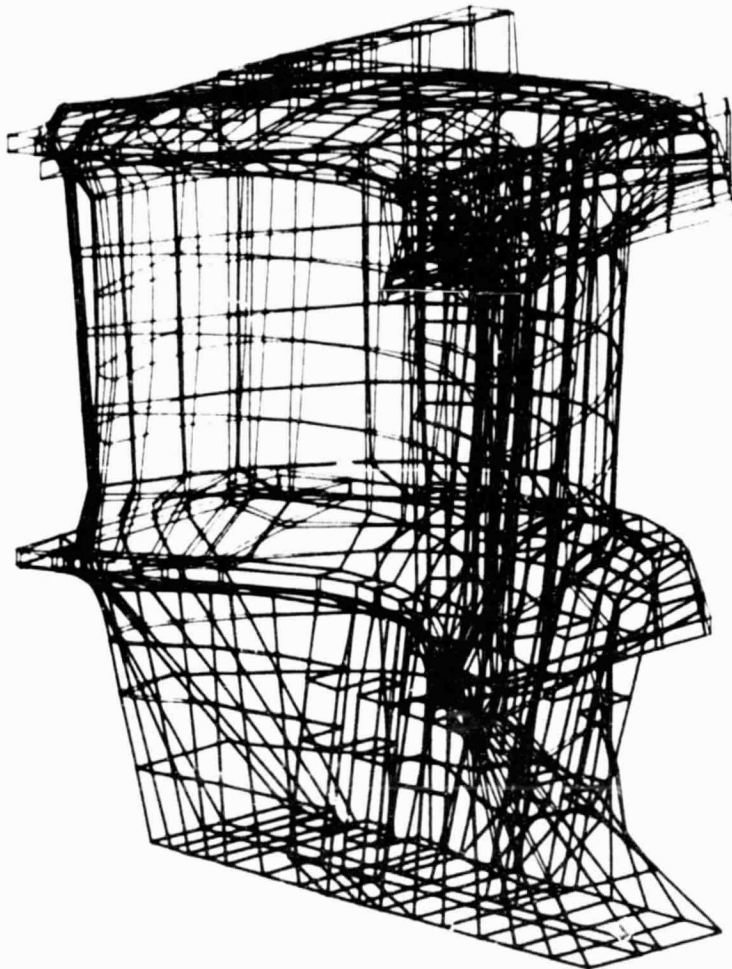


Fig. 2-34 Model 0-1, Mode 8, Freq 51516

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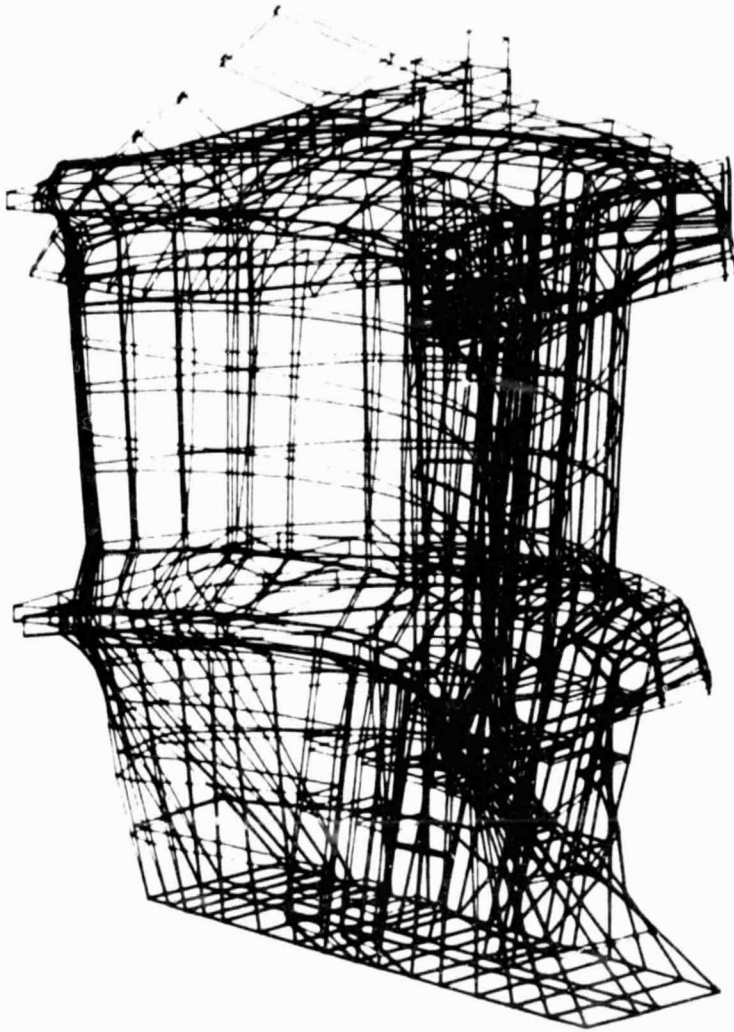


Fig. 2-35 Model 0-1, Mode 9, Freq 60815

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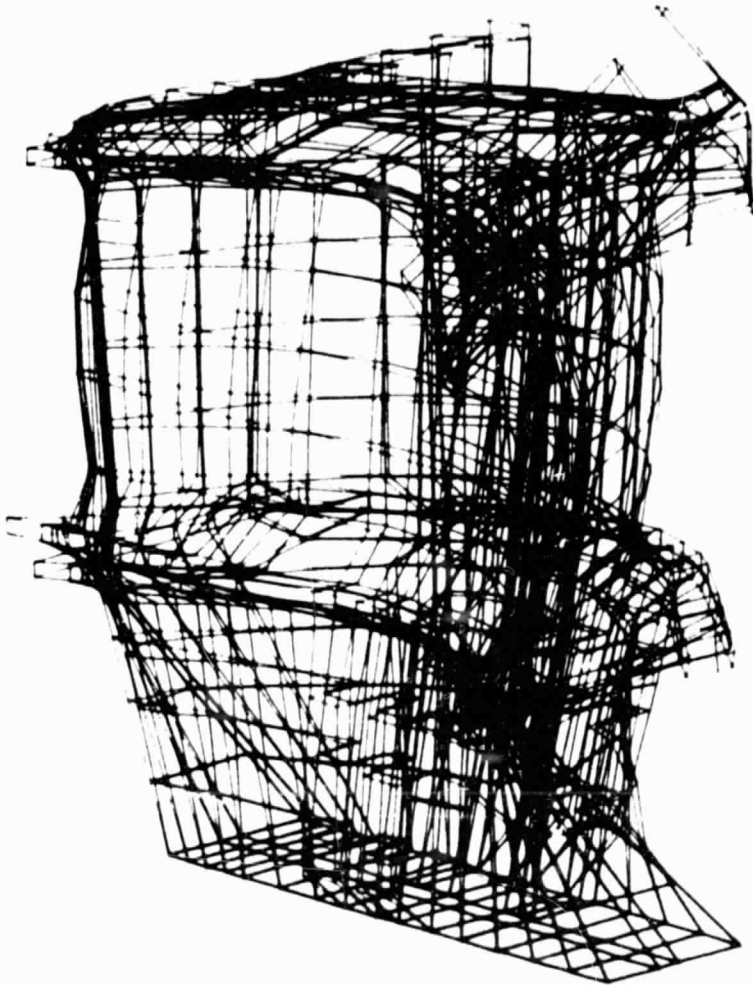


Fig. 2-36 Model O-1, Mode 10, Freq 62167

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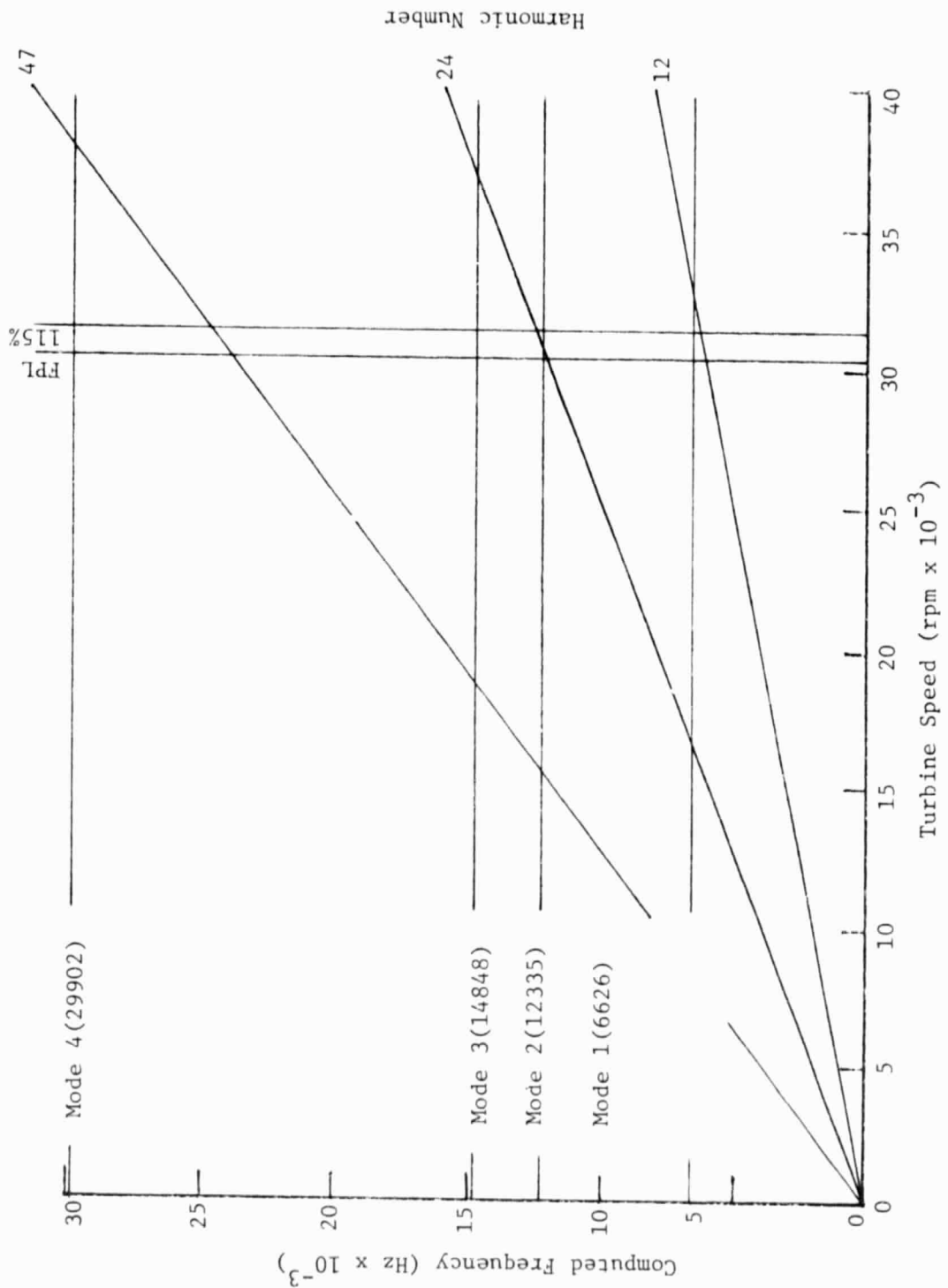


Fig. 2-37 HPOTP First Stage Turbine Blade Campbell Diagram

2.5 HPOTP SECOND STAGE TURBINE BLADE DYNAMICS

The first ten normal modes are summarized in Table 2-4 and Figs. 2-38 through 2-47. The Campbell diagram is shown in Fig. 2-48.

Table 2-4
HPOTP SECOND STAGE TURBINE BLADE NORMAL MODES

<u>Mode</u>	<u>Frequency (Hz)</u>
1	4478
2	9049
3	11124
4	21677
5	26700
6	33982
7	35694
8	41182
9	46274
10	47398

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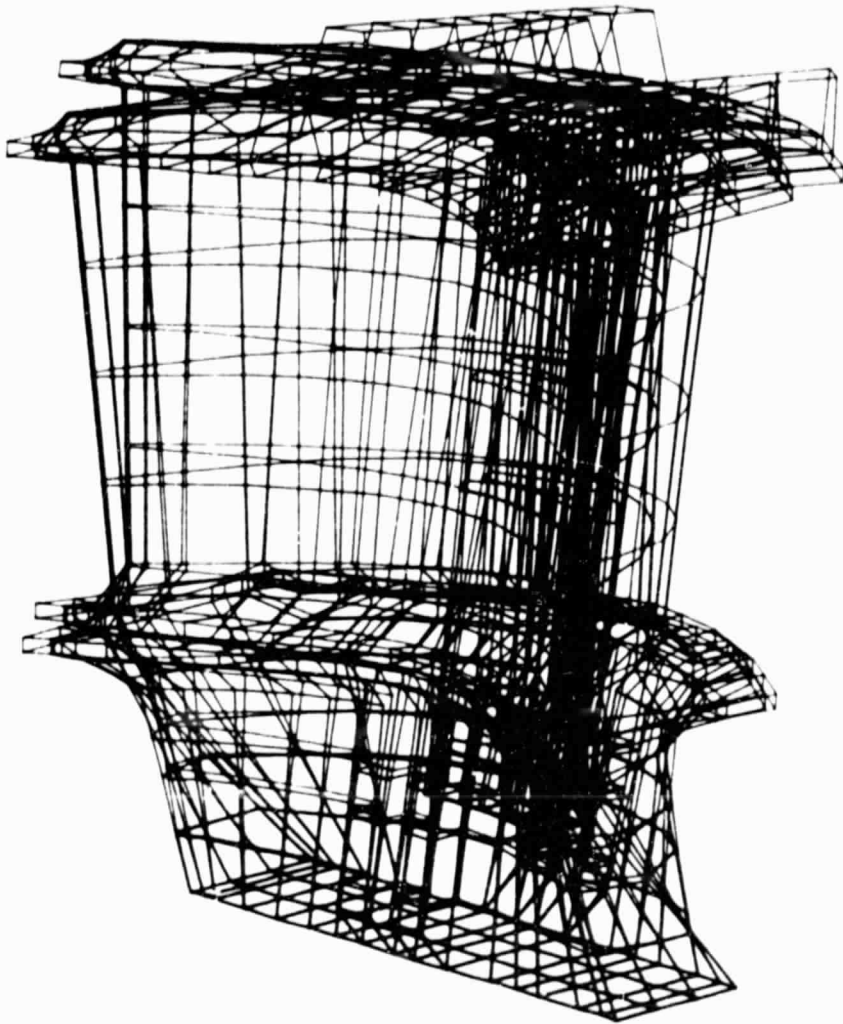


Fig. 2-38 Model O-2, Mode 1, Freq 4478

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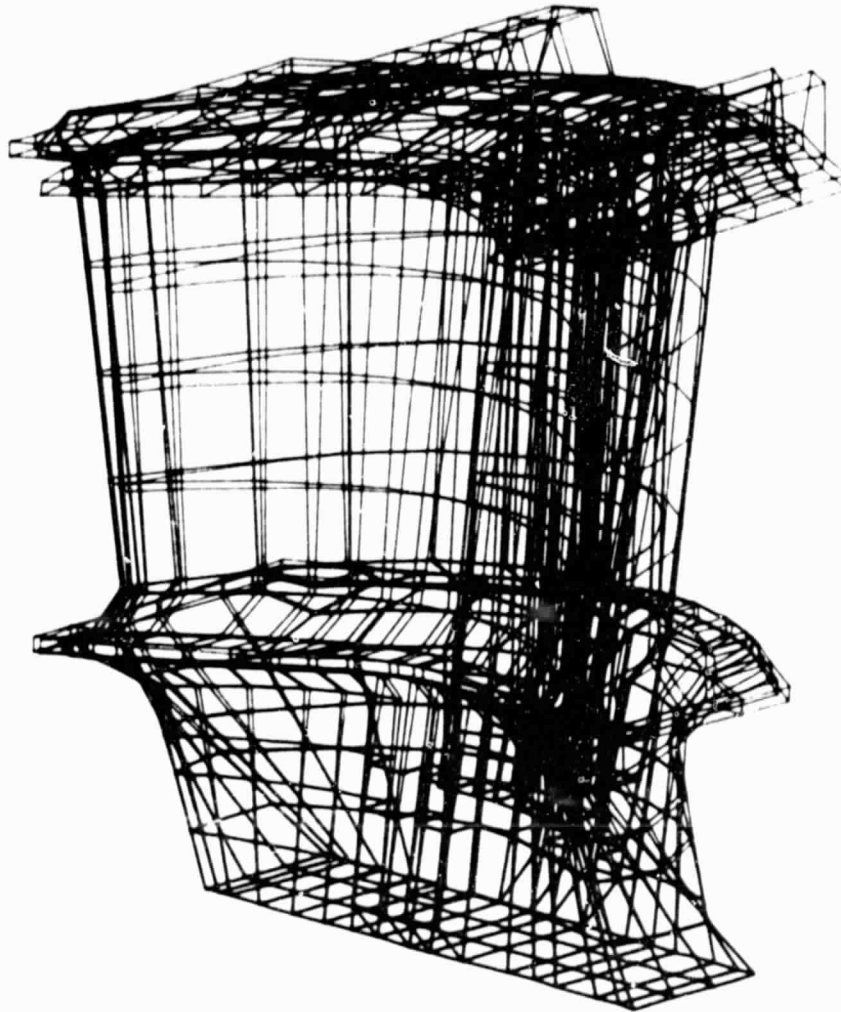


Fig. 2-39 Model O-2, Mode 2, Freq 9049

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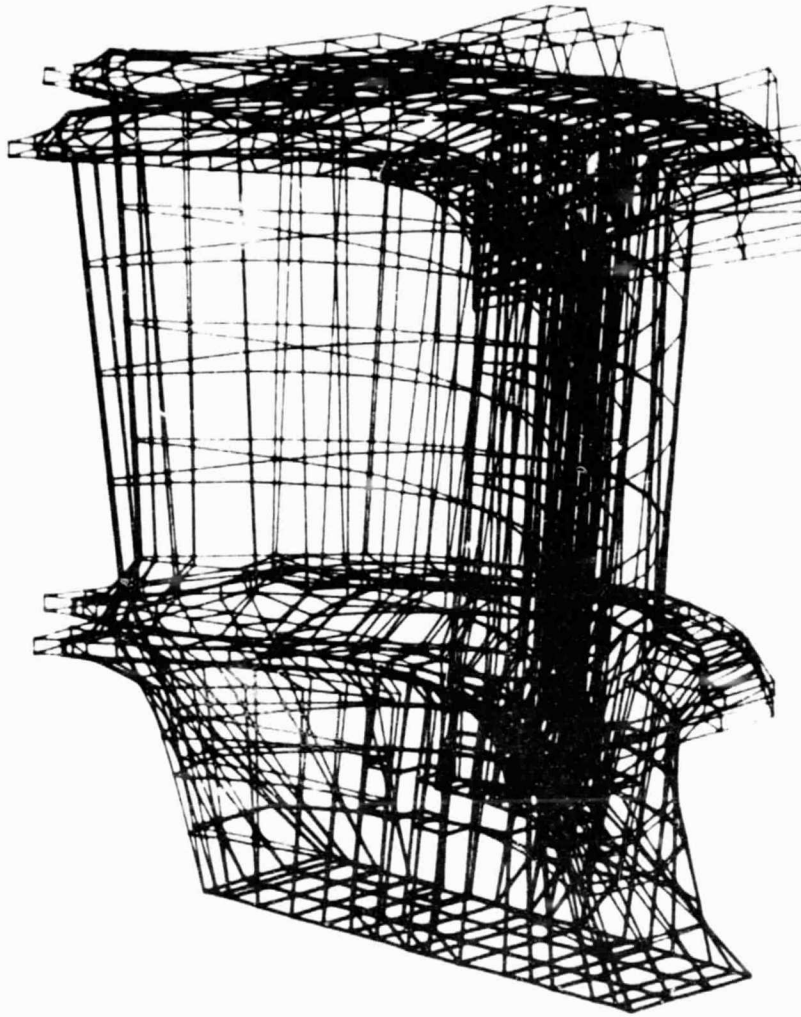


Fig. 2-40 Model O-2, Mode 3, Freq 11124

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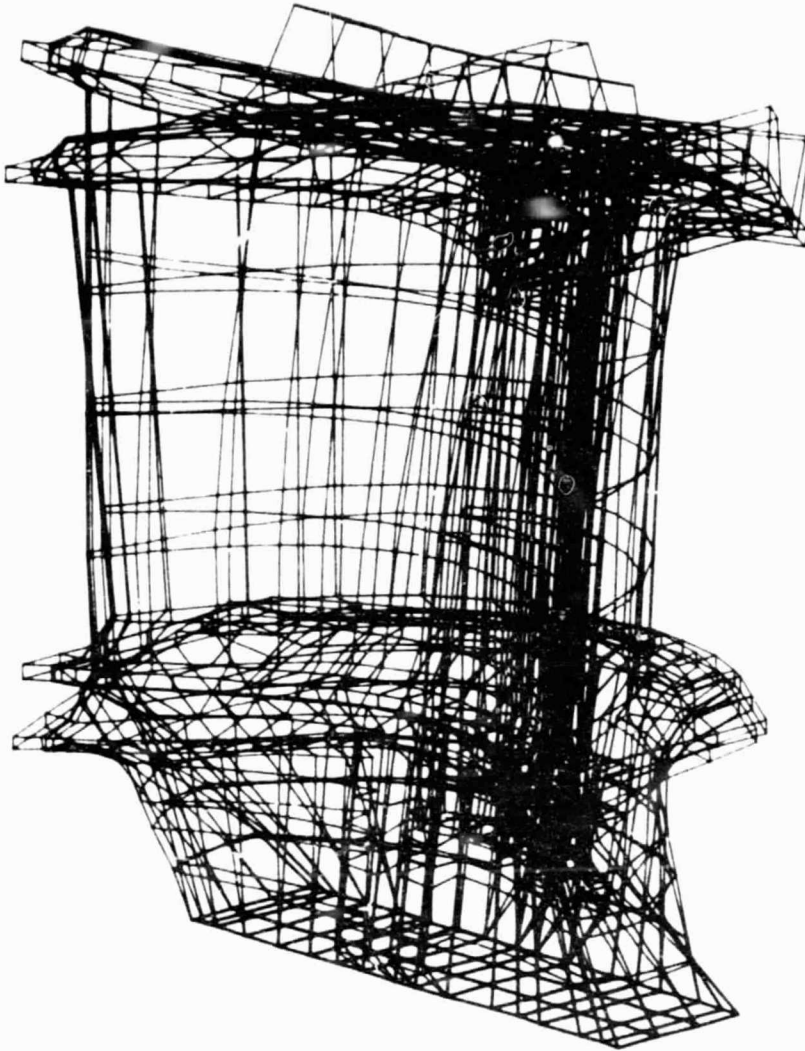


Fig. 2-41 Model O-2, Mode 4, Freq 21677

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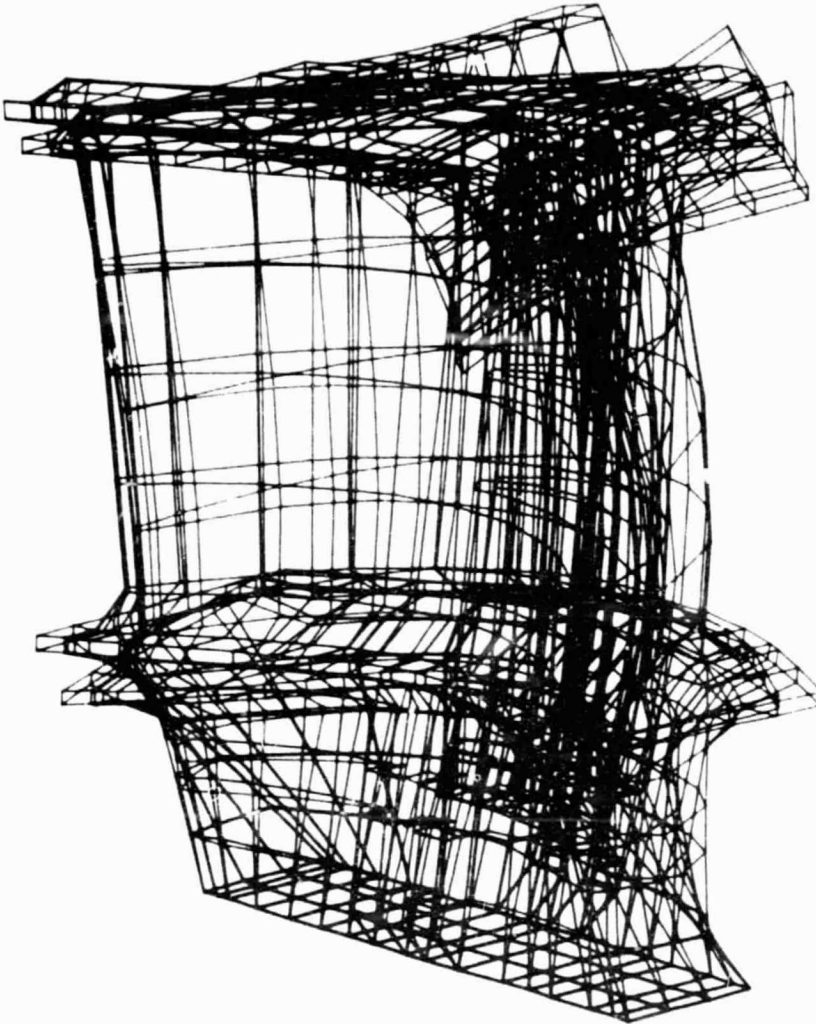


Fig. 2-42 Model 0-2, Mode 5, Freq 26700

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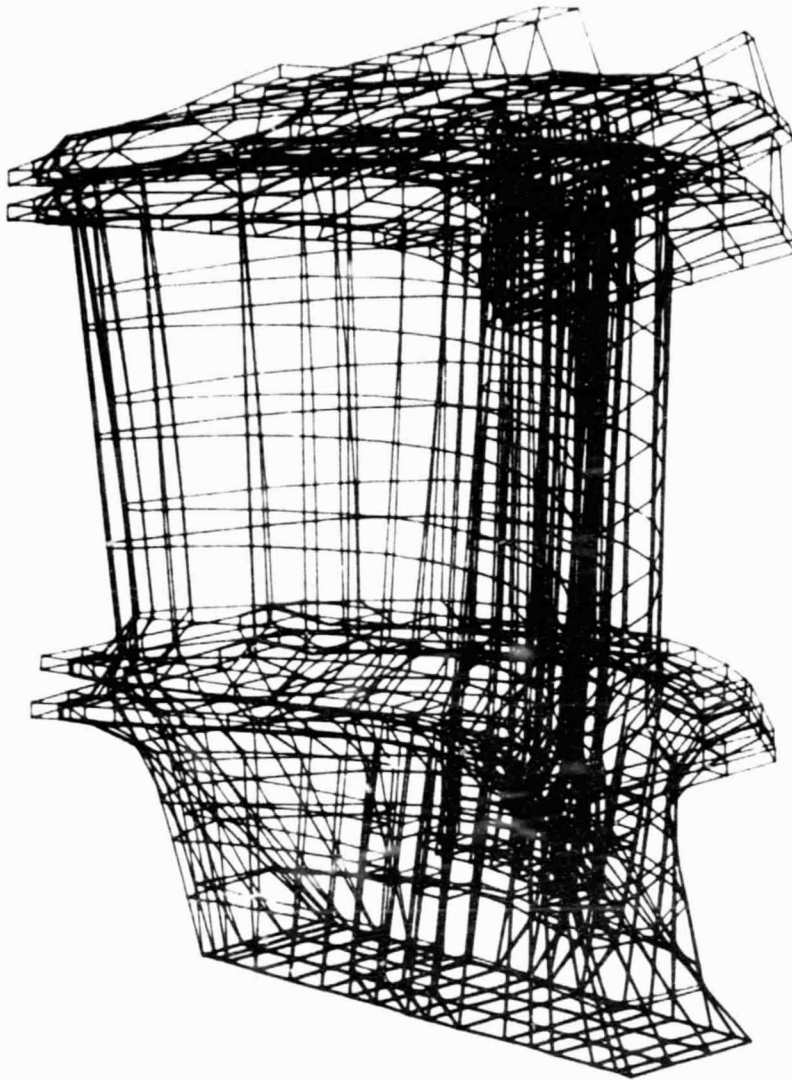


Fig. 2-43 Model 0-2, Mode 6, Freq 33982

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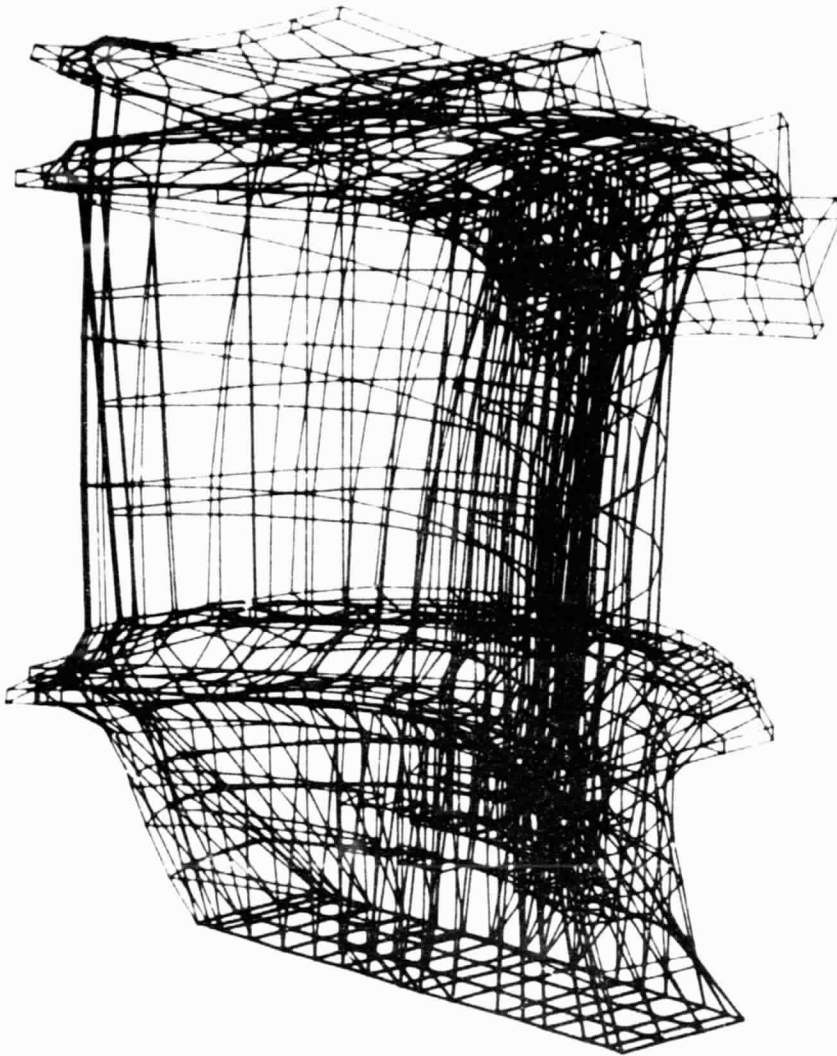


Fig. 2-44 Model O-2, Mode 7, Freq 35694

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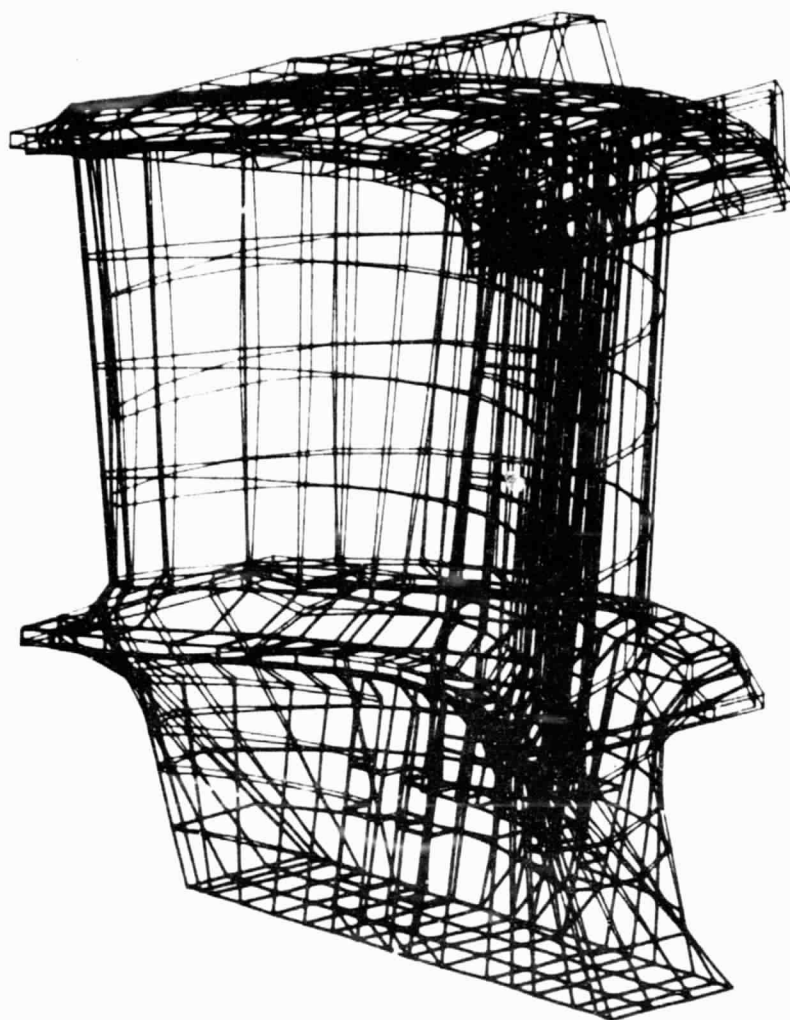


Fig. 2-45 Model 0-2, Mode 8, Freq 41182

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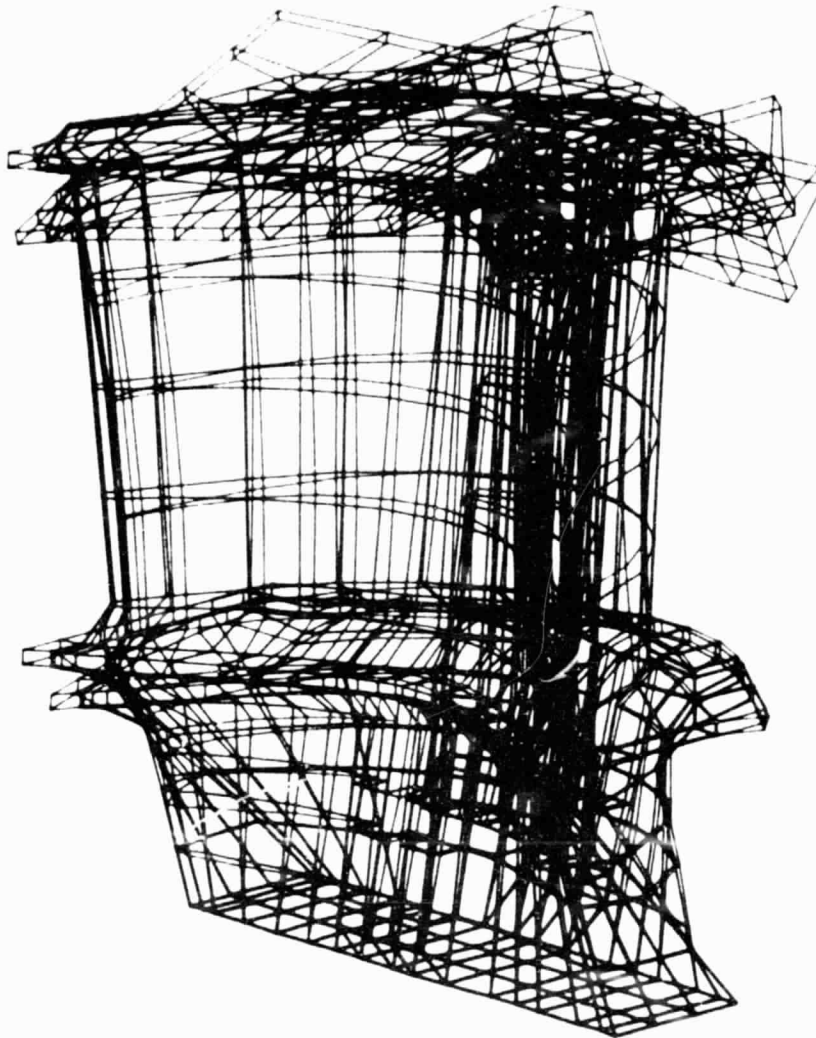


Fig. 2-46 Model 0-2, Mode 9, Freq 46274

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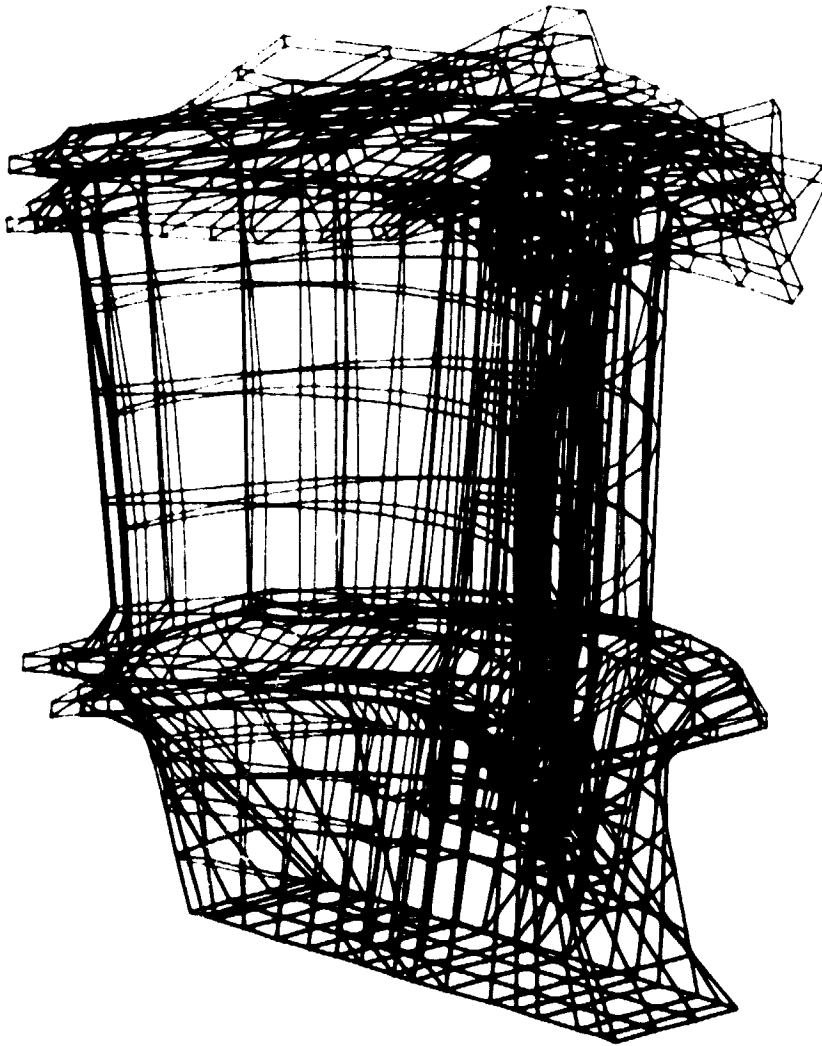


Fig. 2-47 Model 0-2, Mode 10, Freq 47398

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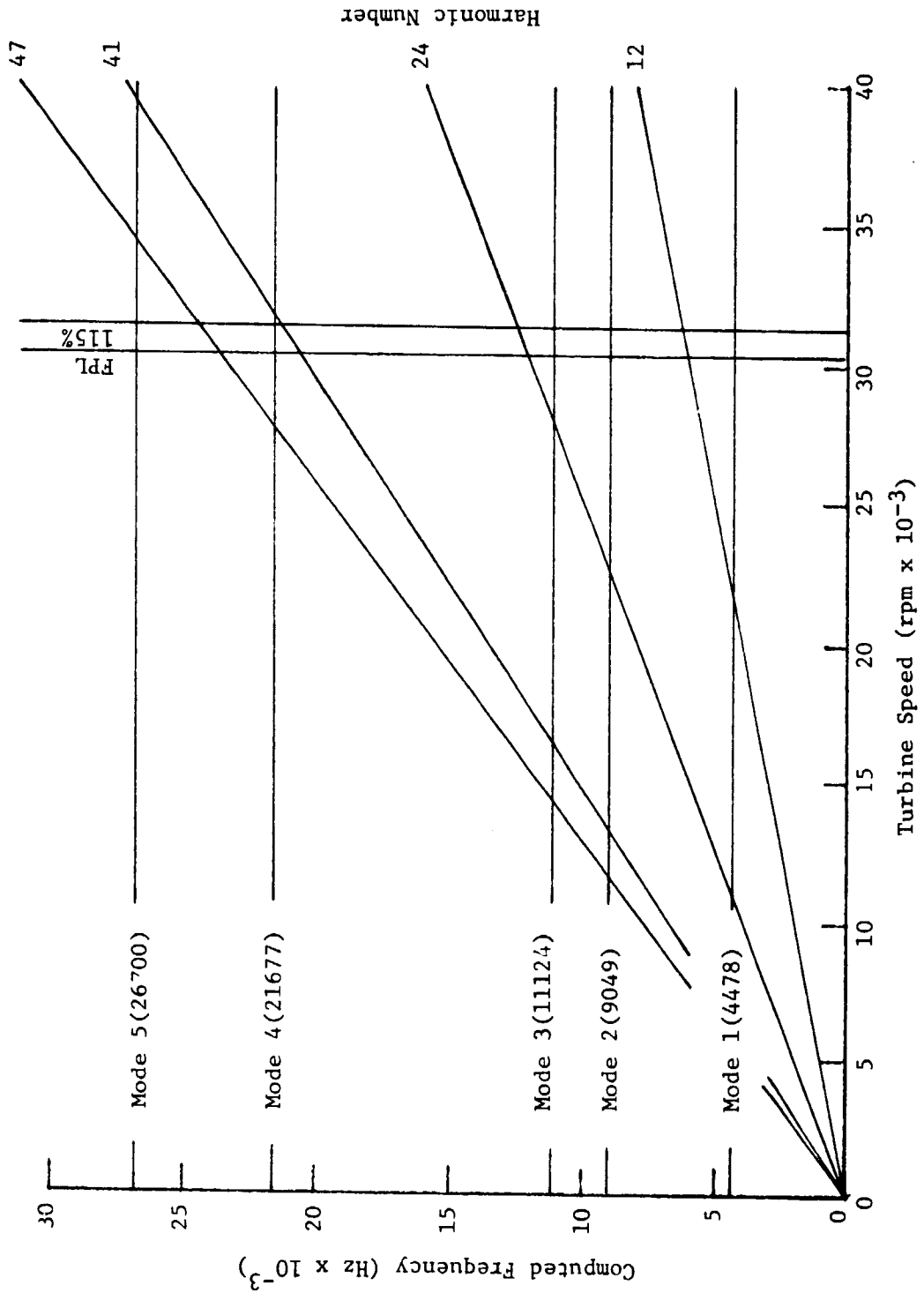


Fig. 2-48 HPOTP Second Stage Turbine Blade Campbell Diagram

3. SSME NOZZLE DYNAMICS

The lower modes of the nozzles are summarized in Table 3-1 and Figs. 3-14 through 3-56. For brevity, the components are identified in tables and figures as follows:

- F1 - First Stage Fuel Nozzle
- F2 - Second Stage Fuel Nozzle
- O1 - First Stage Oxygen Nozzle
- O2 - Second Stage Oxygen Nozzle

No Campbell diagrams are presented due to lack of definition of potential driver. We recognize that further work on these nozzles is desirable to lead to a good knowledge of their dynamics, and recommend that it be performed in the future. This analysis does, however, provide a basis for that projected work and points the direction it should follow.

3.1 SSME NOZZLES - MODEL DESCRIPTION AND SUMMARY OF RESULTS

Four NASTRAN nozzle models were made to simulate airfoil blade segments of the first and second stage HPFTP (F1 and F2 models) and first and second stage HPOTP (O1 and O2 models). The general approach to all four models is the same. Figure 3-1 shows a typical complete nozzle casting.

The grids are defined in rectangular coordinate systems with the Z axis radially outward and with the X axis in the direction of gas flow. The exception is model F2 which has the Y axis in the direction of gas flow. The displacement coordinate system is cylindrical. Fig. 3-2 presents the typical coordinate system arrangement. Figure 3-3 gives the model F2 coordinate system.

Boundary conditions applied to the modeled segments are as follows: constraints on rigid body movement of the whole assembly are placed on the casting support points as shown in Fig. 3-4. Constraints are also made on each point of one cut surface such that it translates equally with its corresponding point on the opposite cut surface. This ensures that the segment acts symmetrically with its implied adjacent segments (Fig. 3-5).

The four models use primarily CIHEX1 elements with CWEDGE and CTETRA elements as required. Grid and element ID number prefixes increase with increasing radius in levels as shown in Figs. 3-5, 3-8, 3-10 and 3-12. Plots showing elements and grids at representative levels follow each figure given.

After the models were executed for normal modes, a processor was run to generate very thin (1×10^{-6} in.) CQUAD1 elements over all exposed surfaces. The grids defining these elements were used to interpolate thermal and pressure data from load source models. The CQUAD1 elements are also used for stress contour plots at each major surface.

Table 3-1
NOZZLE MODEL NORMAL MODES SUMMARY

Mode	Model F1 (Hz)	Model F2 (Hz)	Model O1 (Hz)	Model O2 (Hz)
1	3466	2726	3262	3634
2	5599	3371	5445	5006
3	11978	6104	10777	6204
4	13948	14698	11049	7562
5	19017	15955	14505	9176
6	20148	18375	21274	10146
7	26149	21334	23895	11748
8	28266	26211	28514	15554
9	29037	27225	34686	20837
10	-	30403	35871	24911
11	-	-	39171	25737
12	-	-	41348	26562
13	-	-	42090	30007

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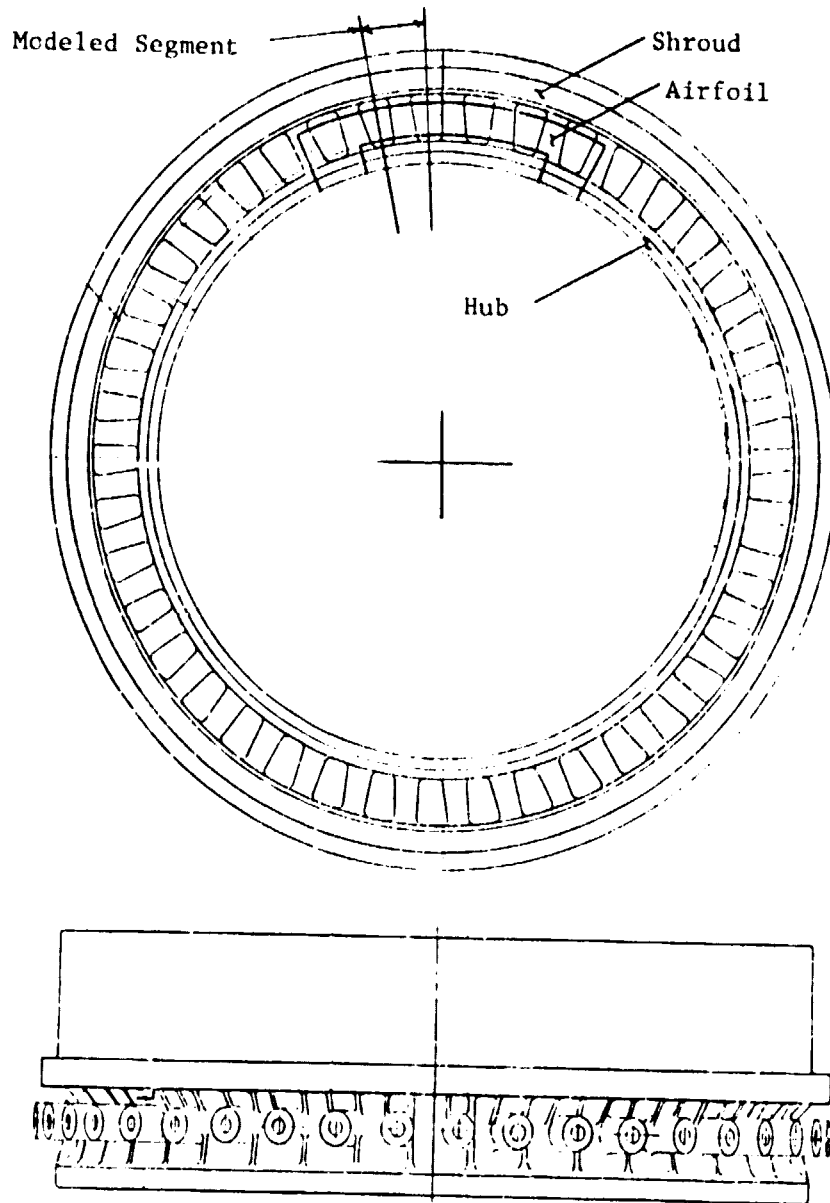


Fig. 3-1 Typical Nozzle Casting Showing Modeled Segment

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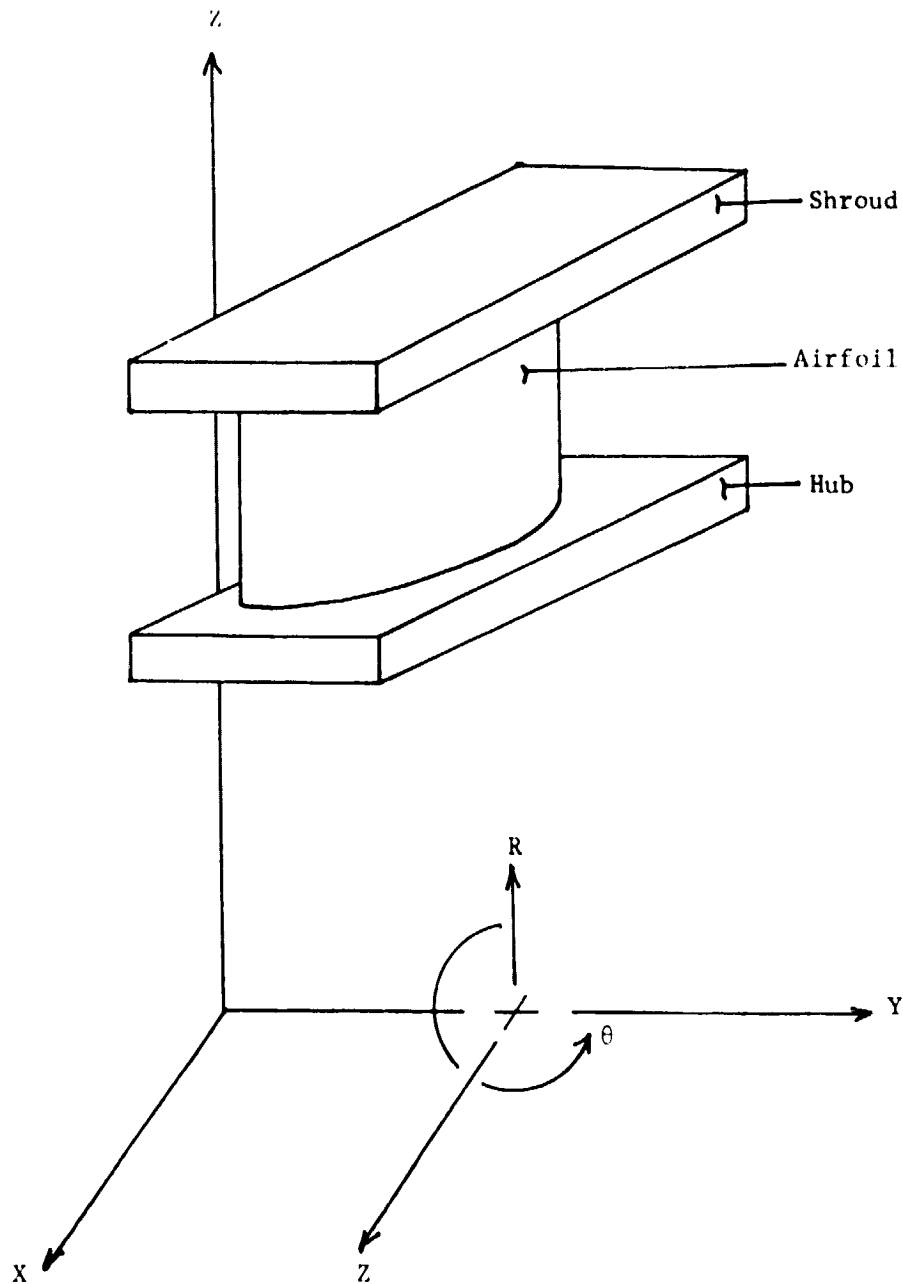


Fig. 3-2 Coordinate Systems for Models F1, O1, and O2

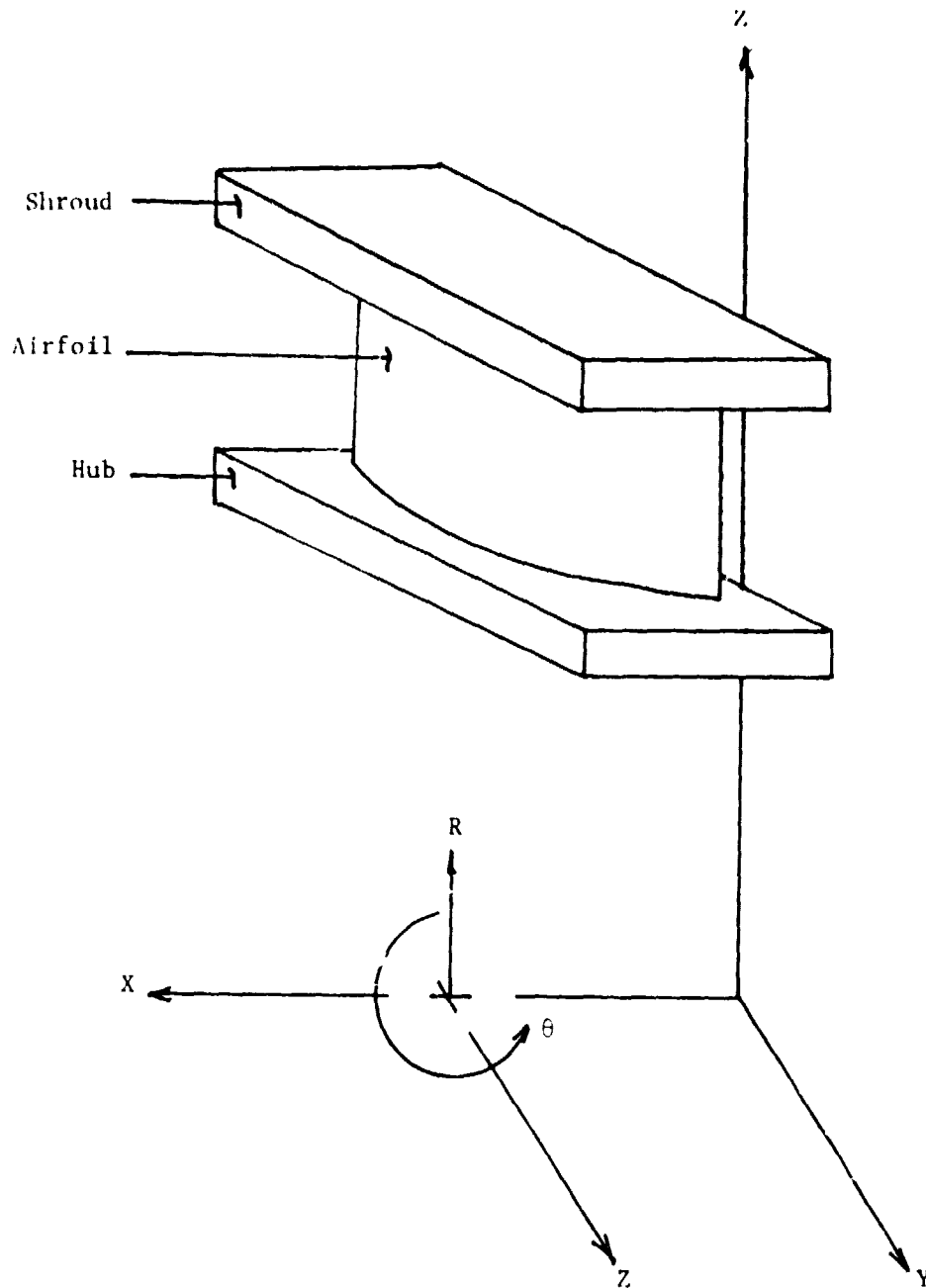


Fig. 3-3 Coordinate System for Model F2

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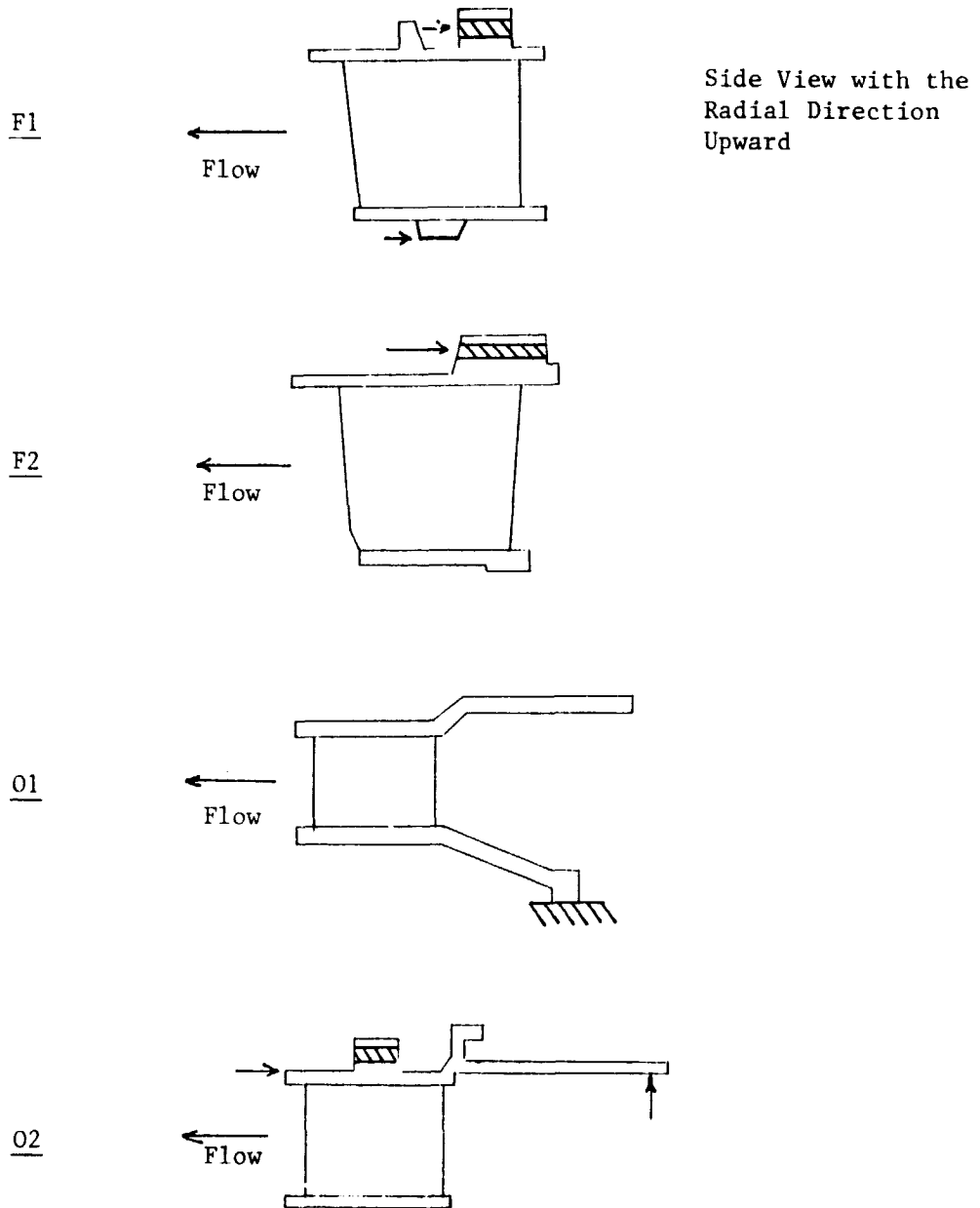
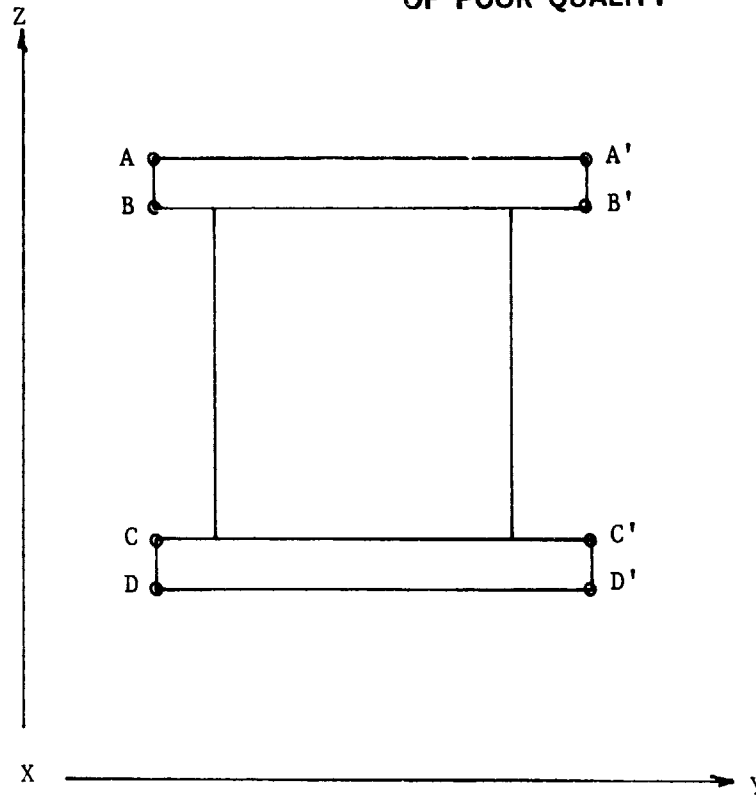


Fig. 3-4 Rigid Body Support Points

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$$\begin{array}{ll} C_{AX} = C_{A'X} & C_{BX} = C_{B'X} \\ C_{AY} = C_{A'Y} & C_{BY} = C_{B'Y} \\ C_{AZ} = C_{A'Z} & C_{BZ} = C_{B'Z} \end{array}$$

$$\begin{array}{ll} C_{CX} = C_{C'X} & C_{DX} = C_{D'X} \\ C_{CY} = C_{C'Y} & C_{DY} = C_{D'Y} \\ C_{CZ} = C_{C'Z} & C_{DZ} = C_{D'Z} \end{array}$$

Fig. 3-5 Coupled Constraints Between Cut Surfaces

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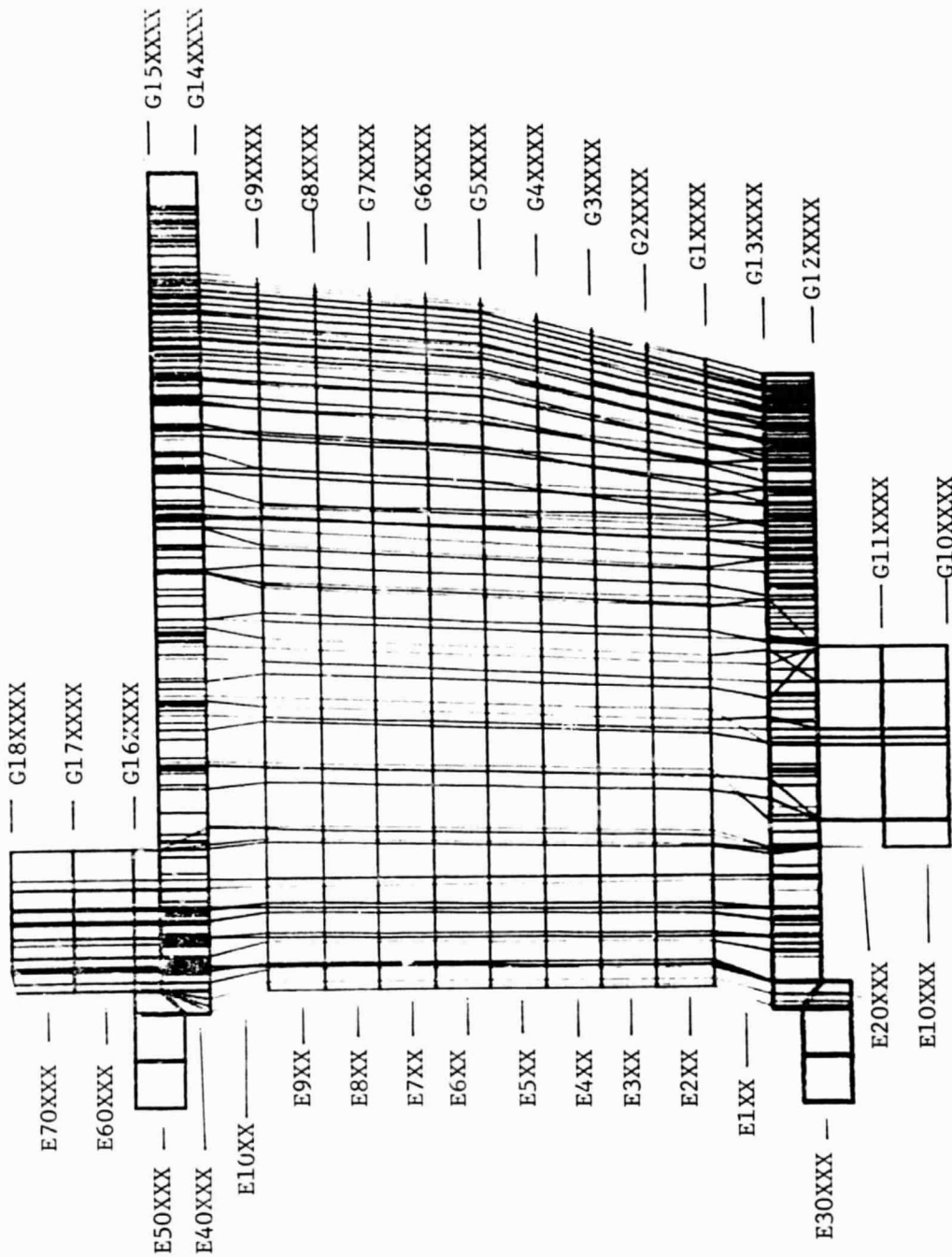


Fig. 3-6 F1 Model Element and Grid Prefixes

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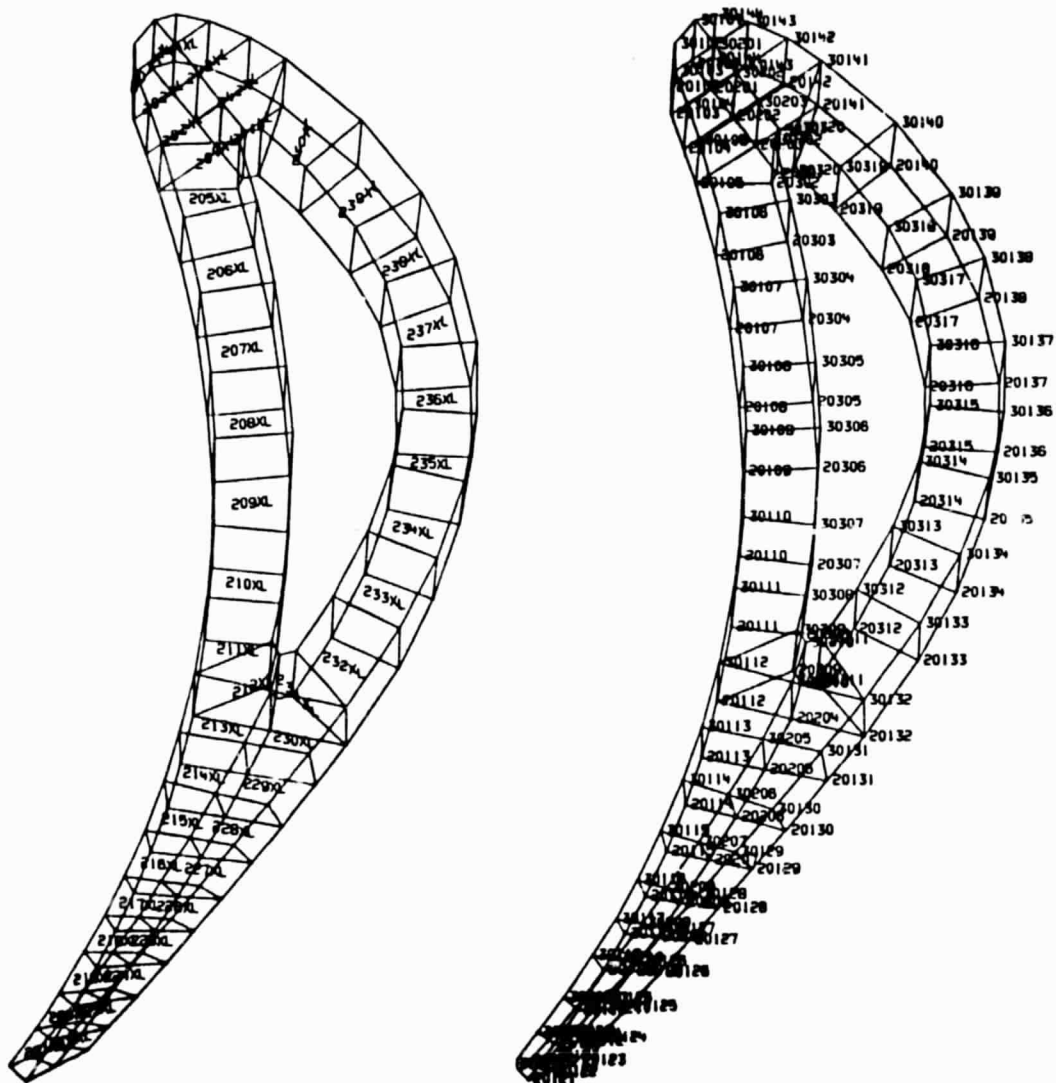


Fig. 3-7 F1 Model Representative Airfoil Section

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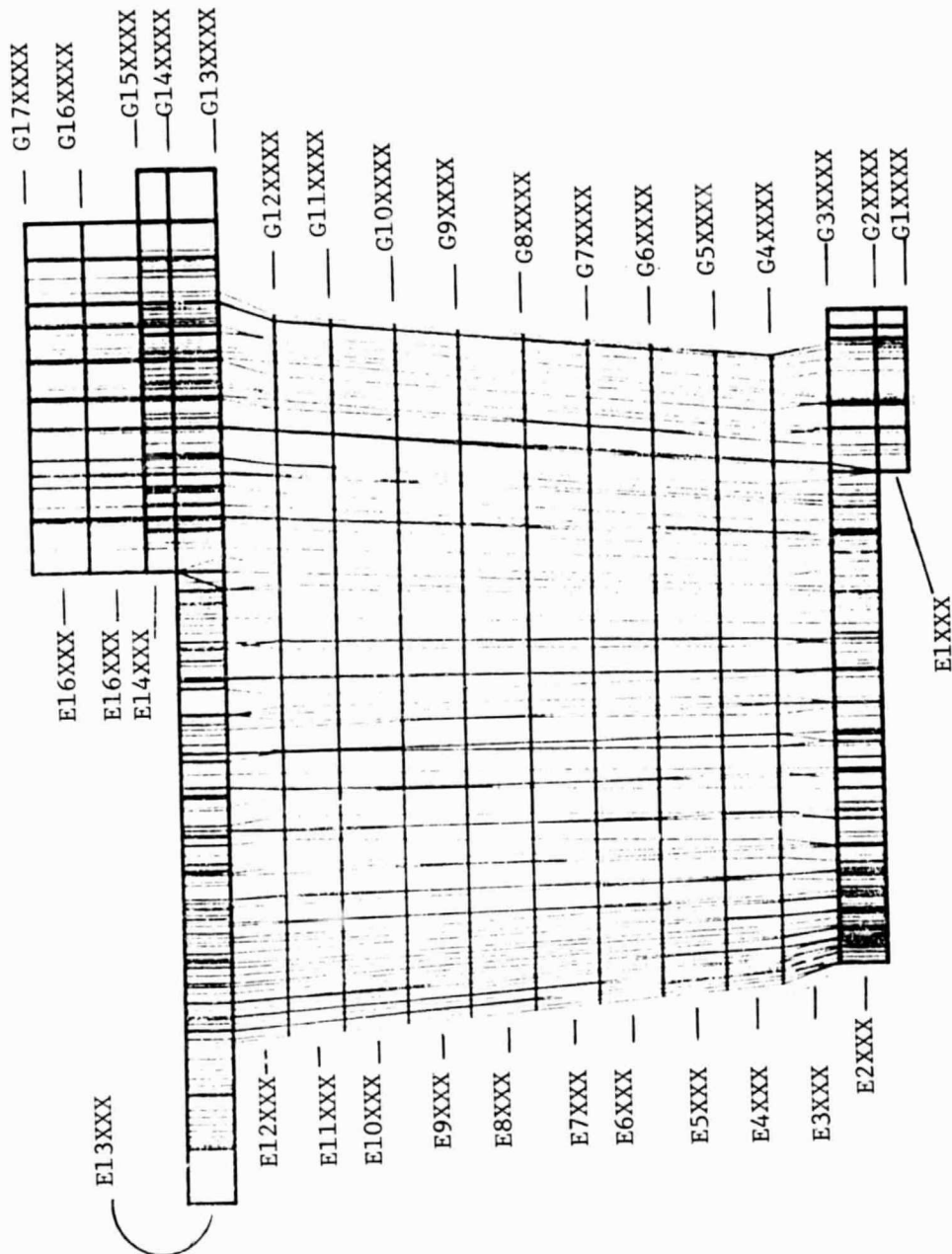


Fig. 3-8 F2 Model Element and Grid ID Prefixes

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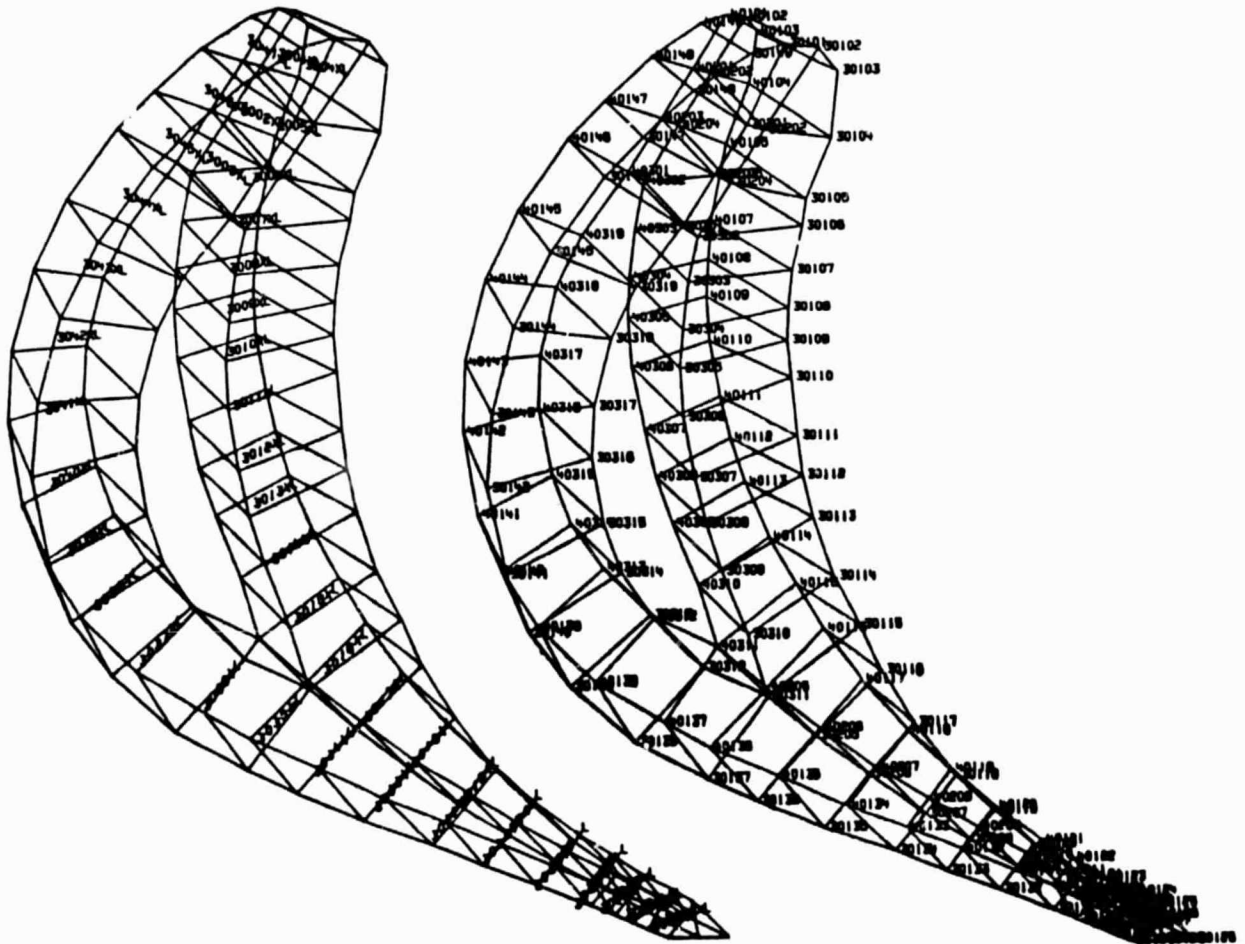


Fig. 3-9 F-2 Model Representative Airfoil Section

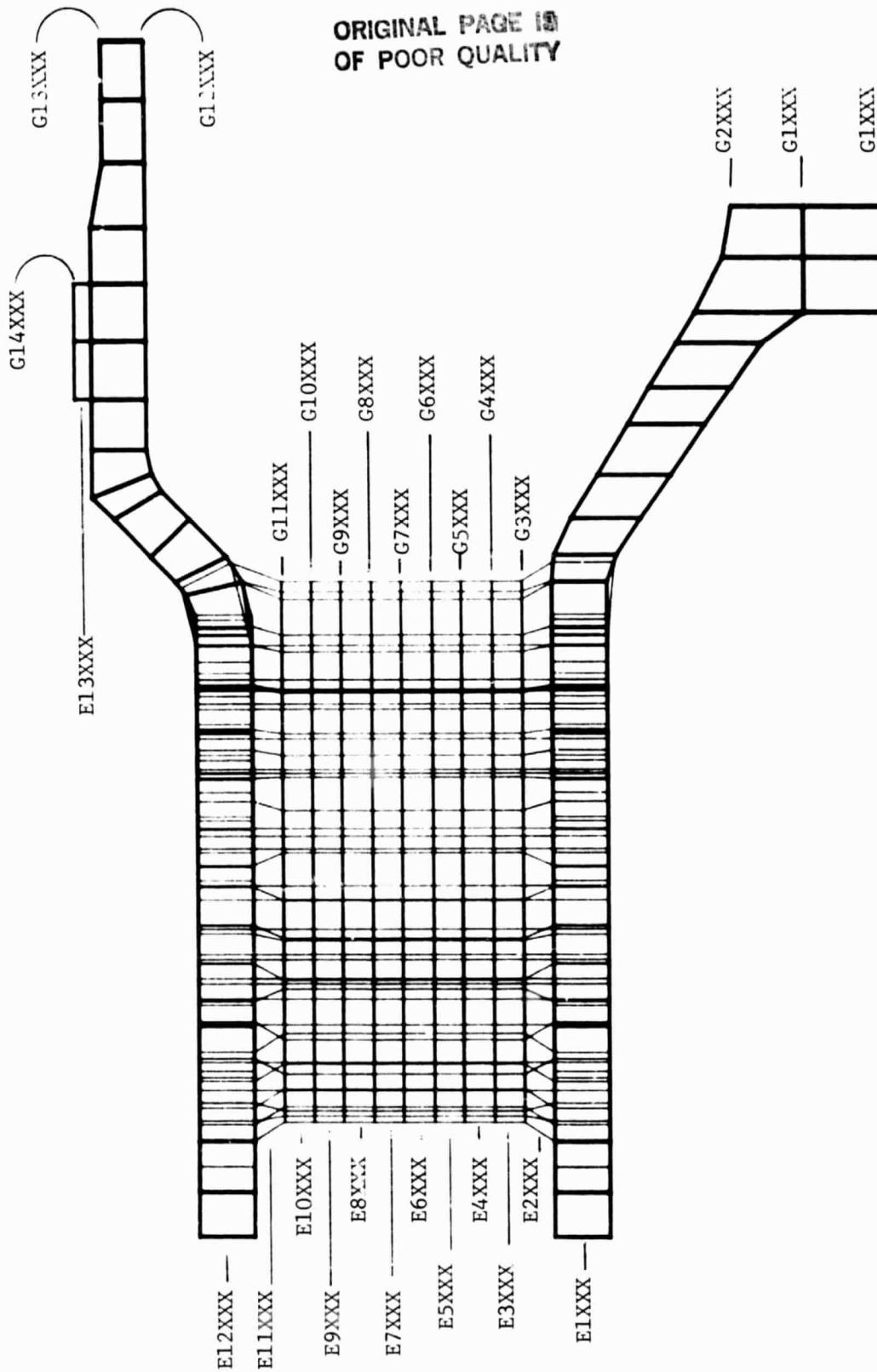


Fig. 3-10 01 Model Element and Grid Prefixes

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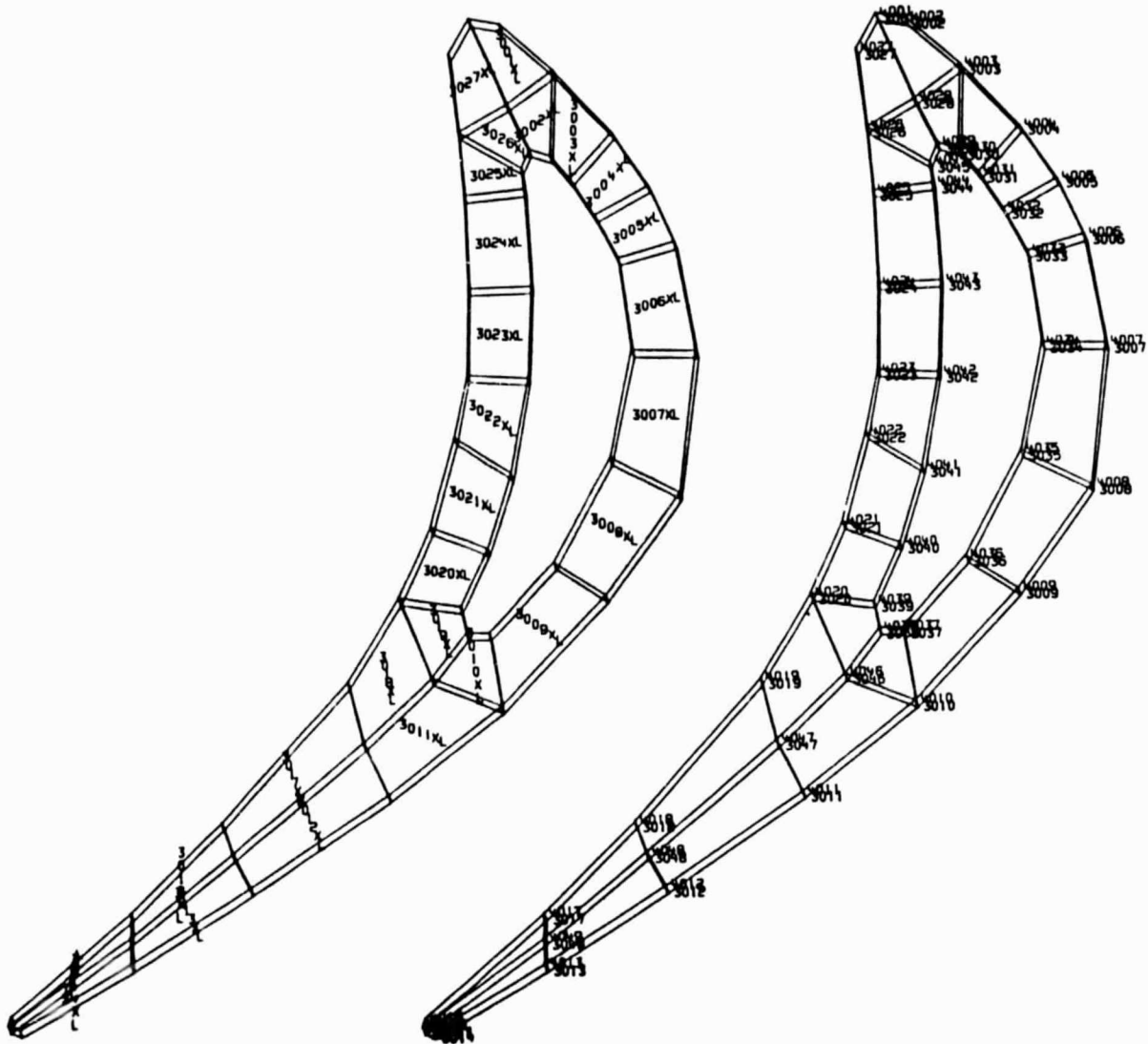


Fig. 3-11 O1 Model Representative Section

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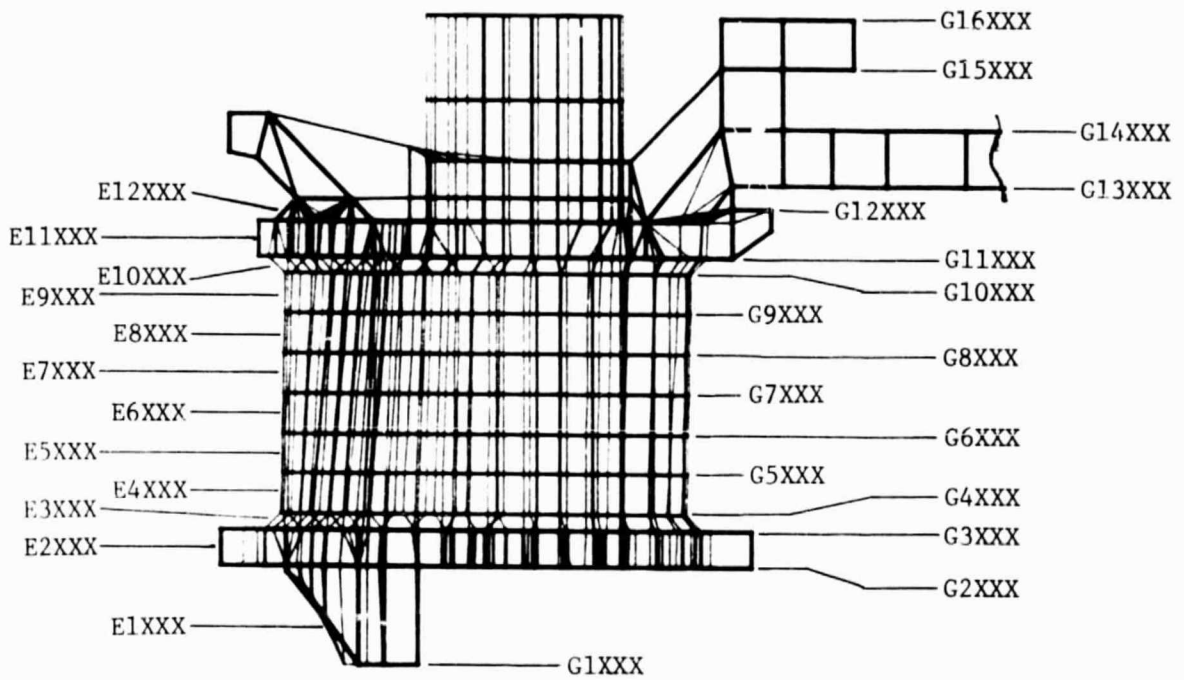


Fig. 3-12 02 Model Element and Grid Prefixes

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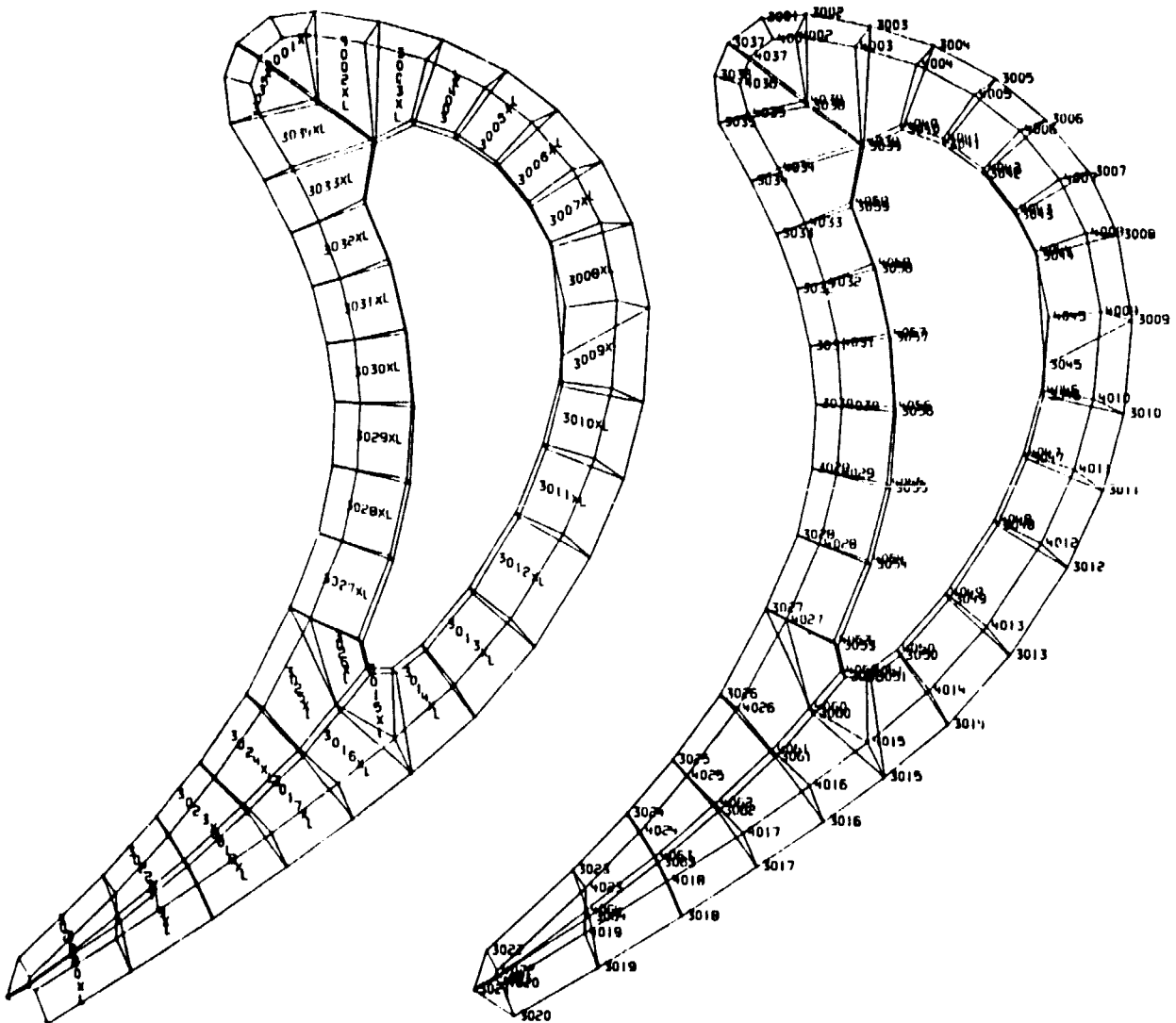


Fig. 3-13 02 Model Representative Section

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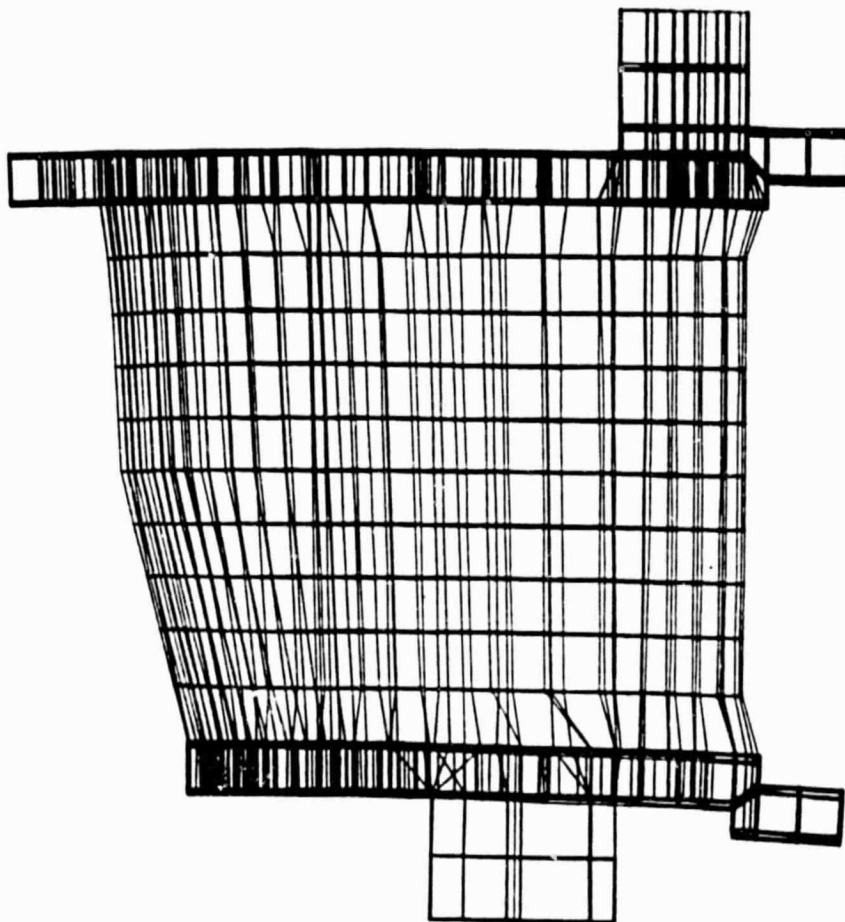


Fig. 3-14 Model F1, Mode 1, Freq 3467

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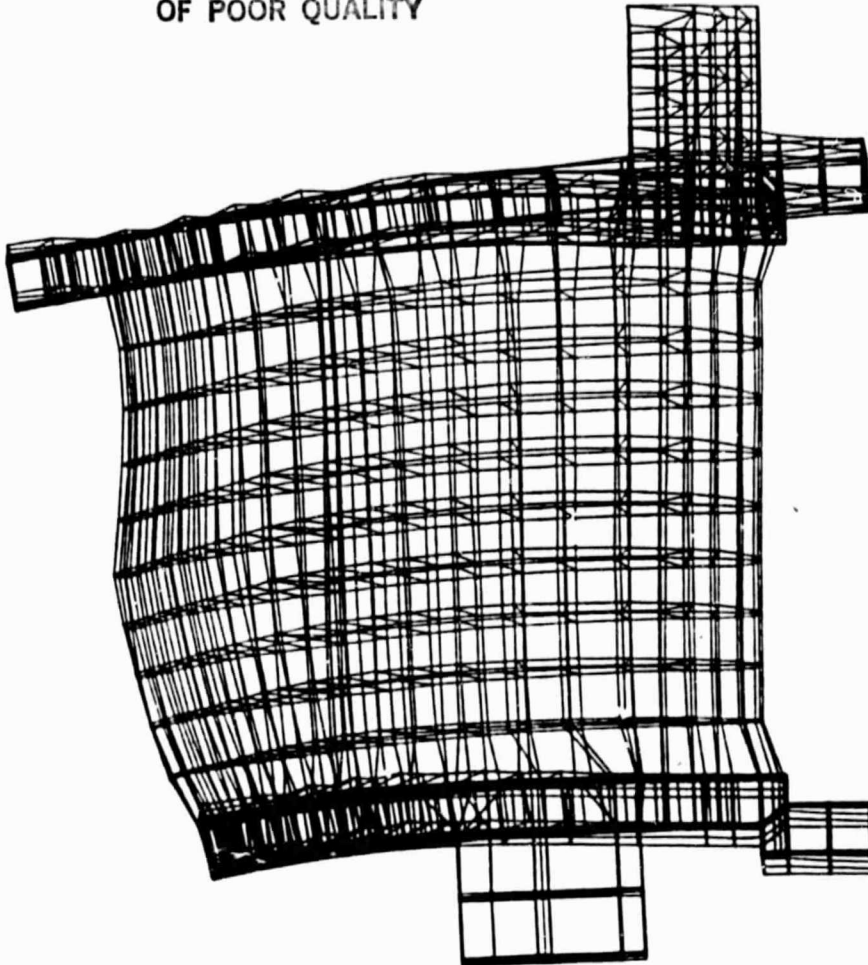


Fig. 3-15 Model F1, Mode 2, Freq 5599

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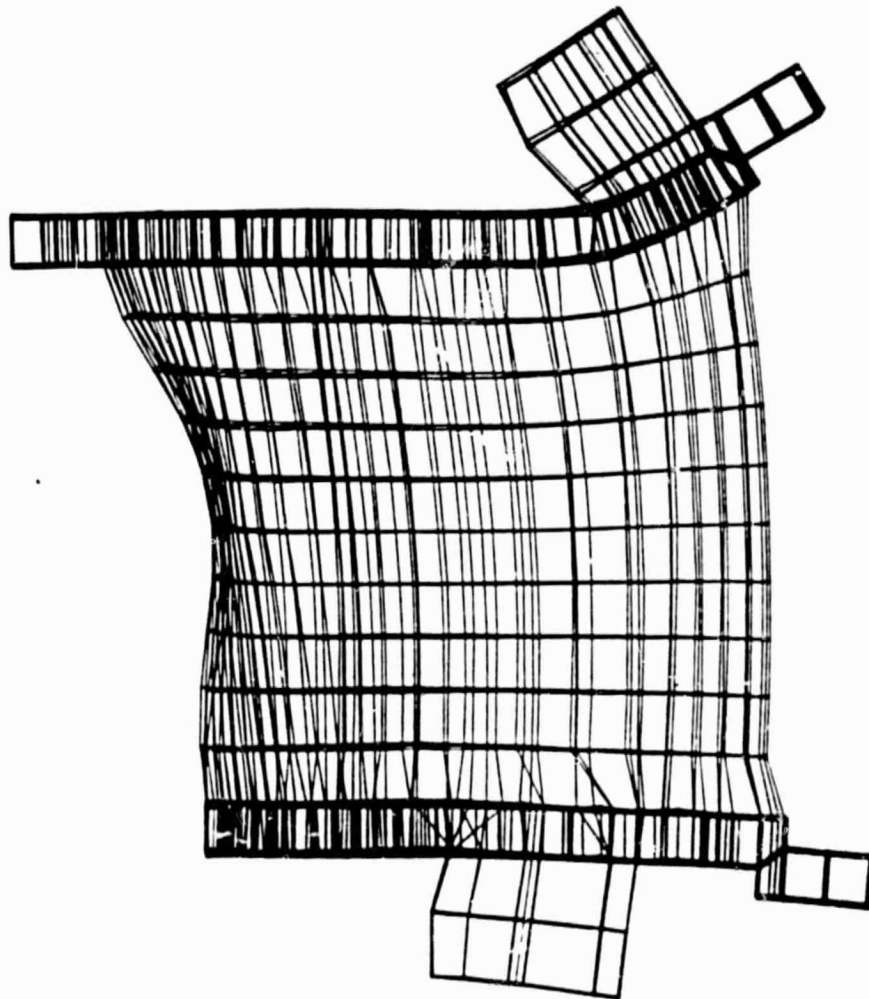


Fig. 3-16 Model F1, Mode 3, Freq 11987

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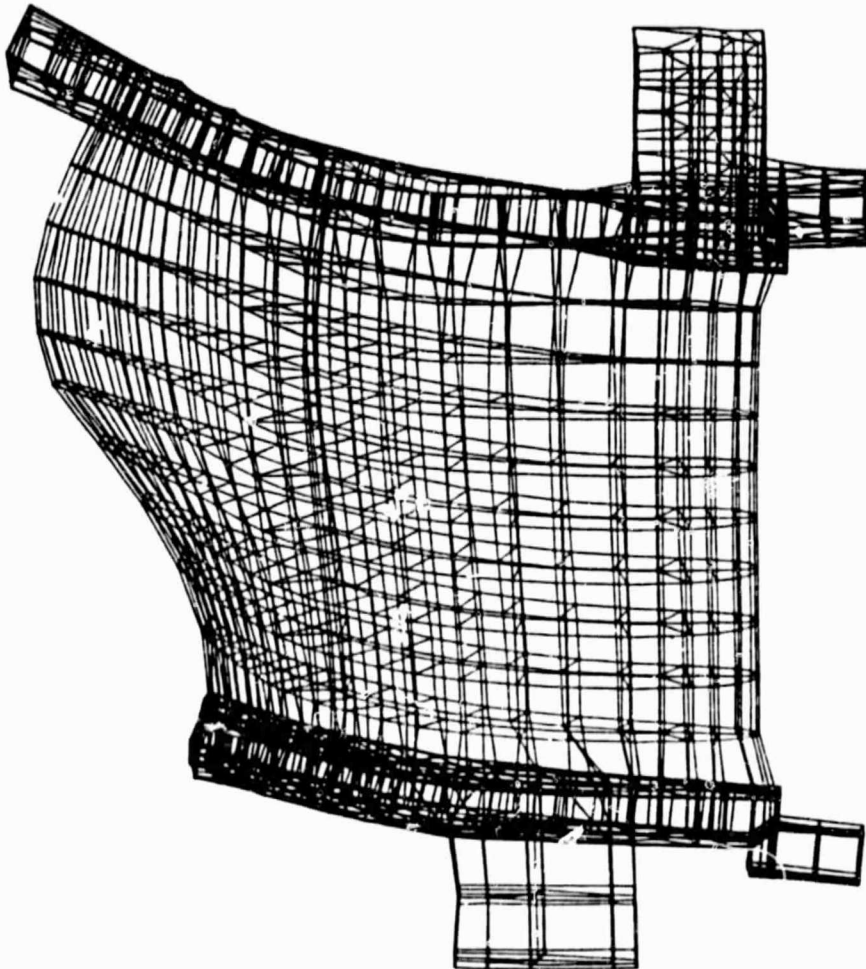


Fig. 3-17 Model F1, Mode 4, Freq 13948

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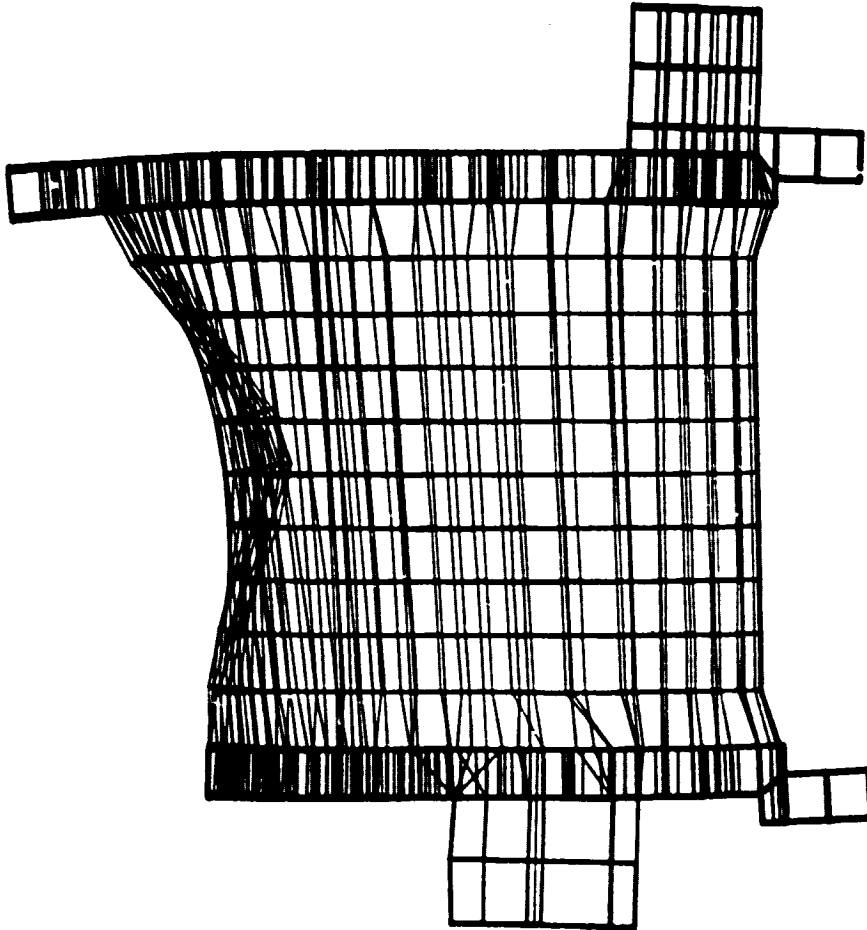


Fig. 3-18 Model F1, Mode 5, Freq 19017

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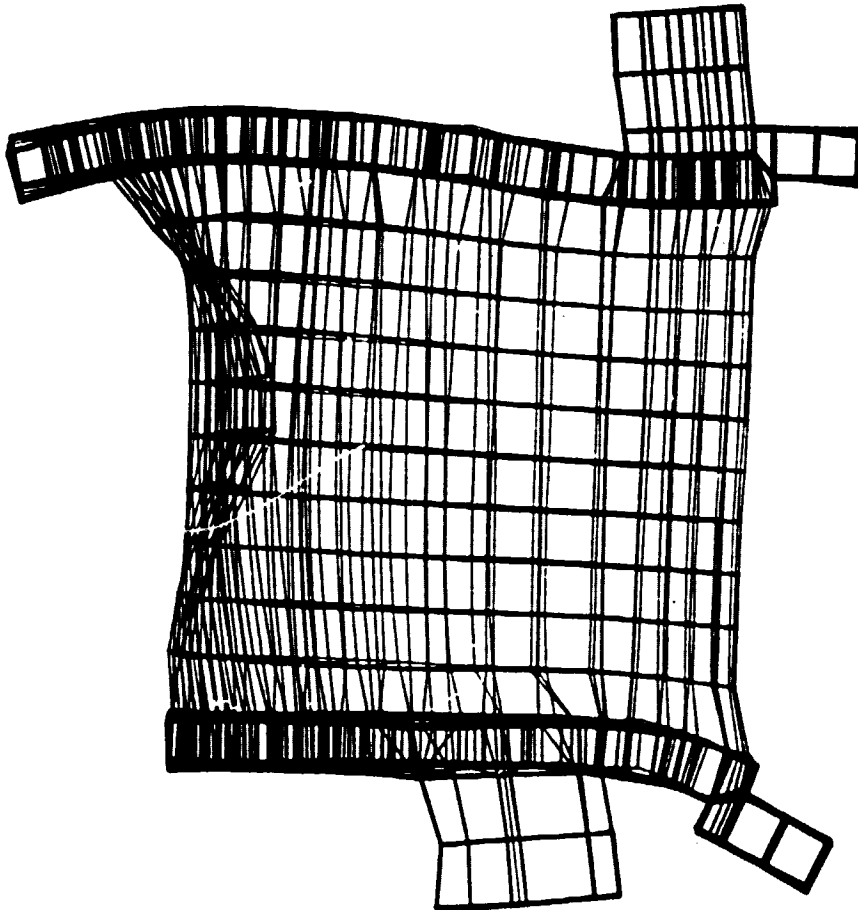


Fig. 3-19 Model F1, Mode 6, Freq 20148

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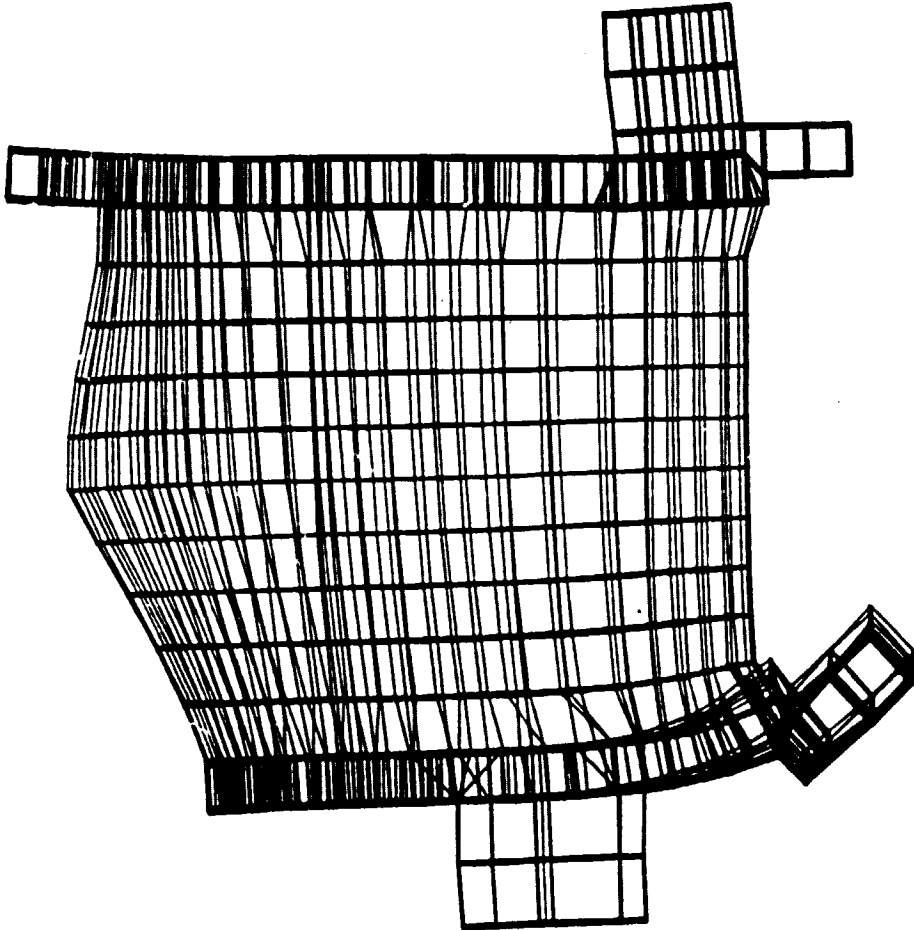


Fig. 3-20 Model F1, Mode 7, Freq 26149

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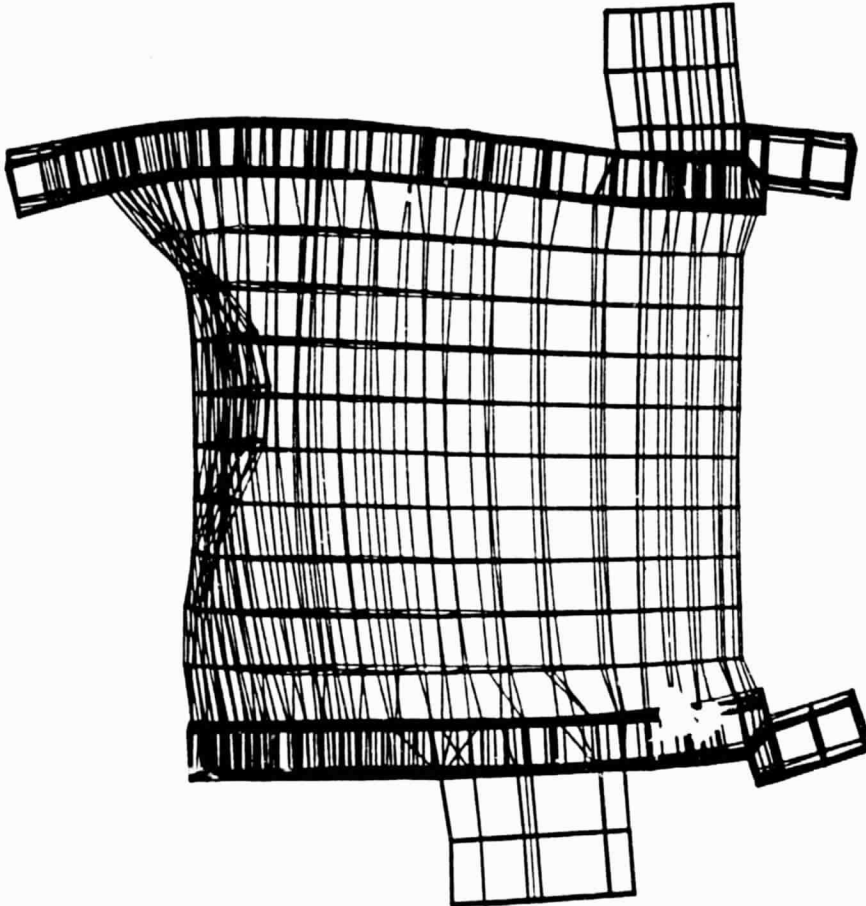


Fig. 3-21 Model F1, Mode 8, Freq 28266

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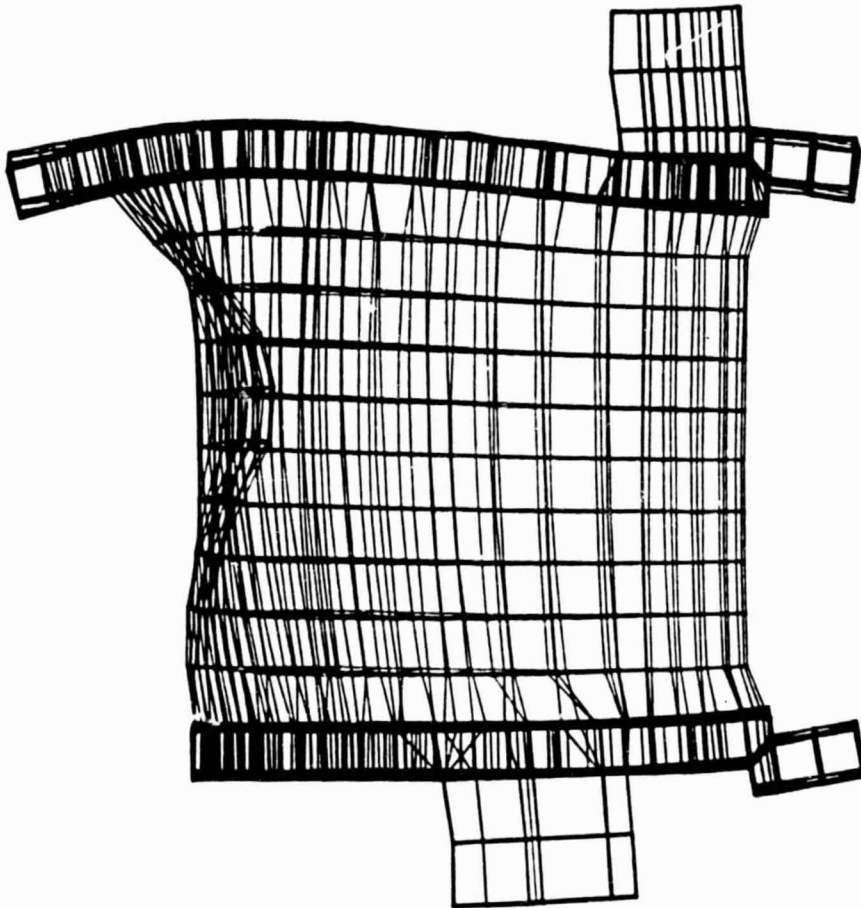


Fig. 3-22 Model F1, Mode 9, Freq 29037

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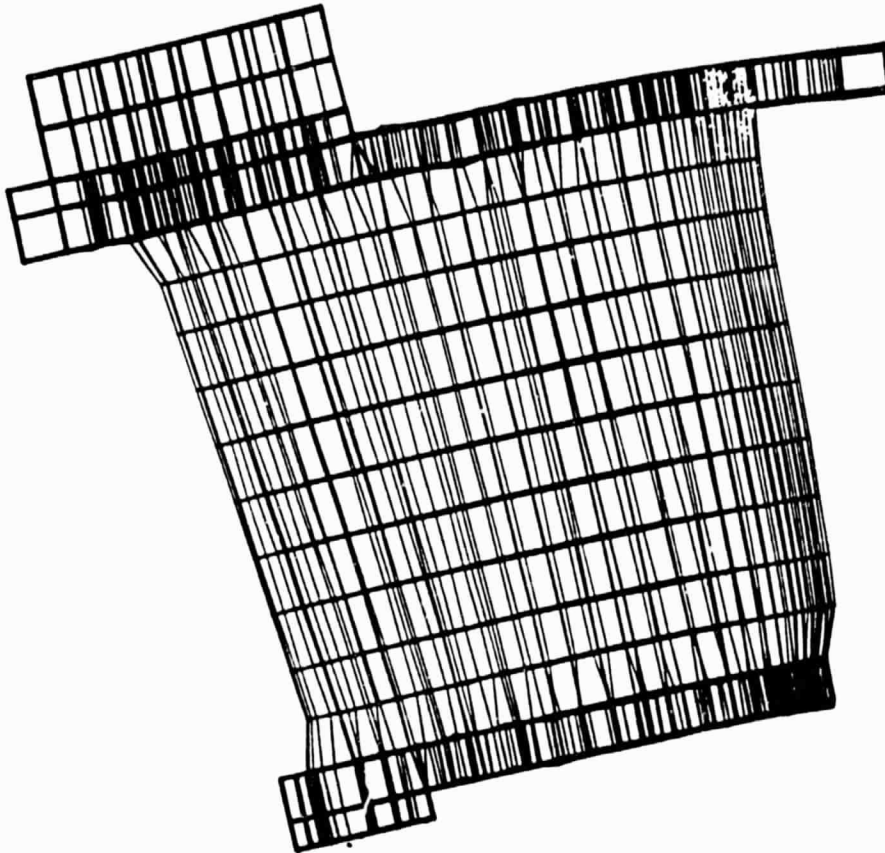


Fig. 3-23 Model F2, Mode 1, Freq 2726

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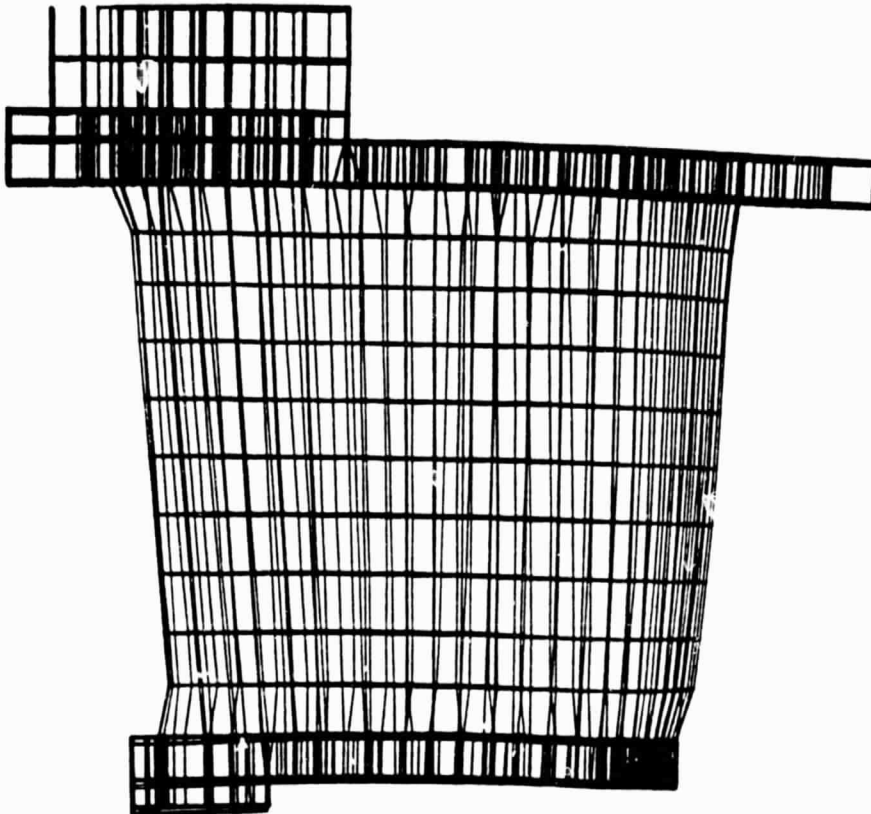


Fig. 3-24 Model F2, Mode 2, Freq 3371

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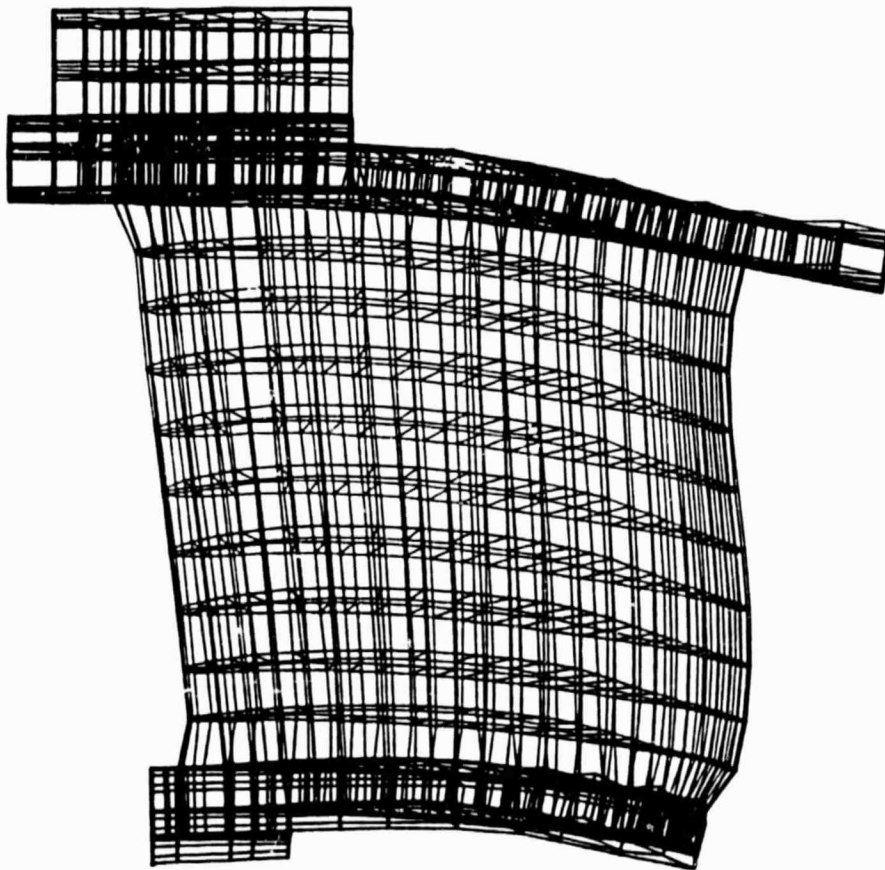


Fig. 3-25 Model F2, Mode 3, Freq 6104

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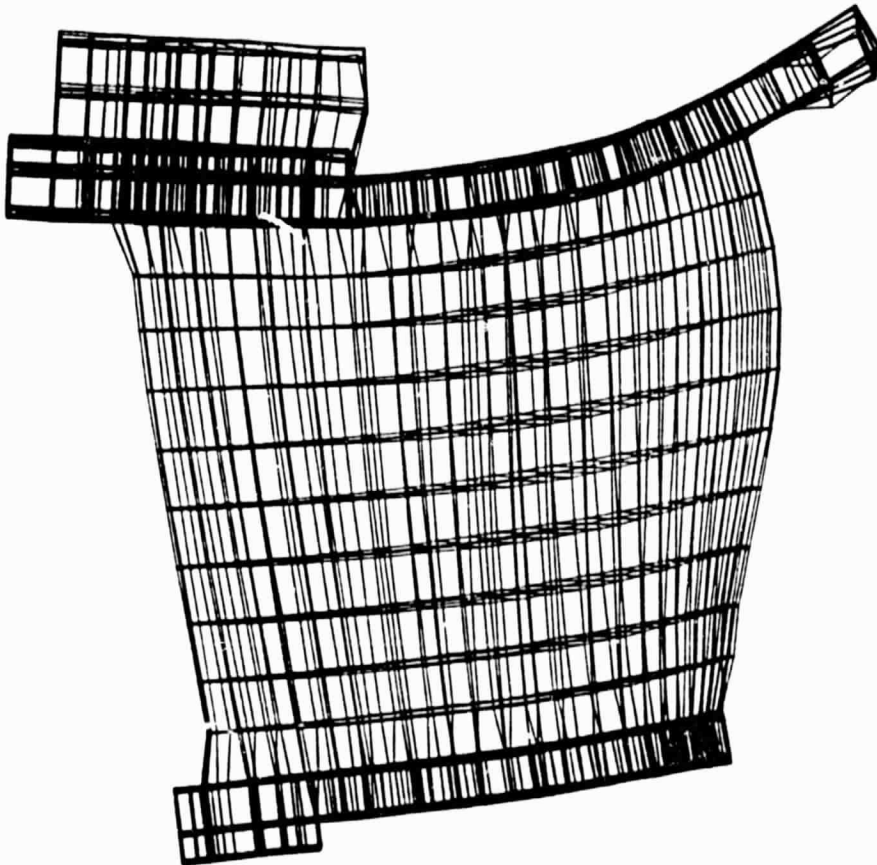


Fig. 3-26 Model F2, Mode 4, Freq 14698

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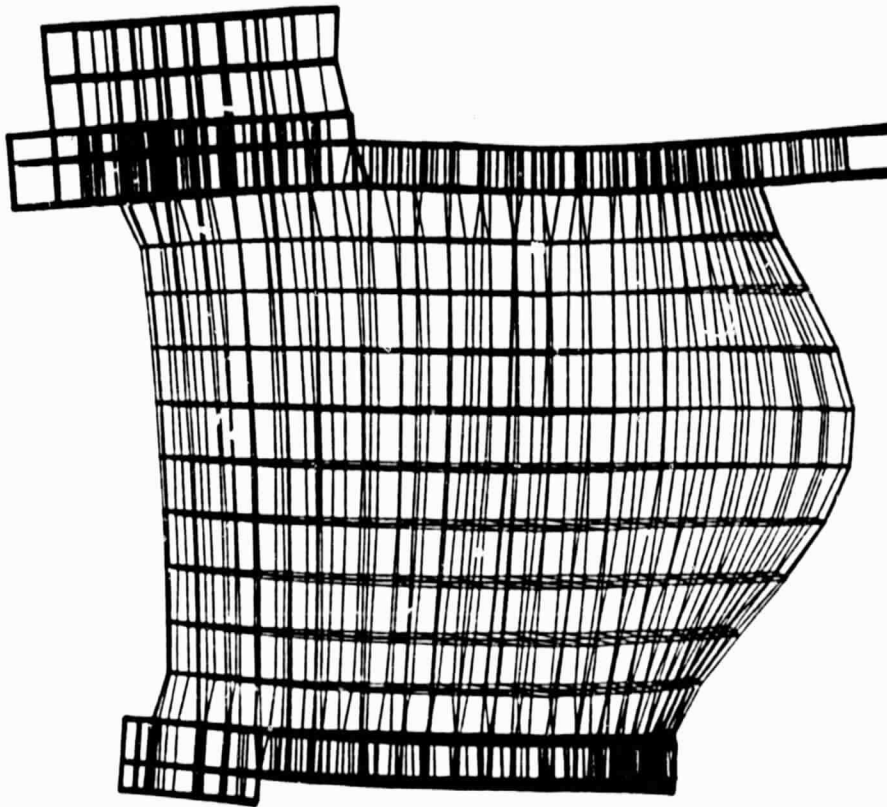


Fig. 3-27 Model F2, Mode 5, Freq 15955

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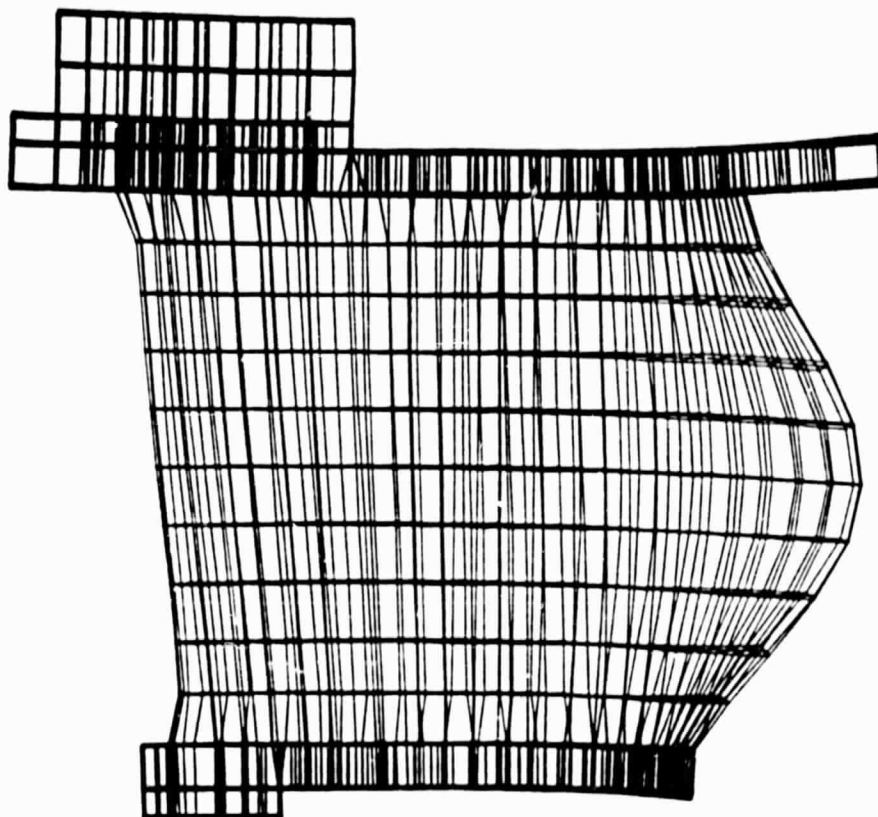


Fig. 3-28 Model F2, Mode 6, Freq 18375

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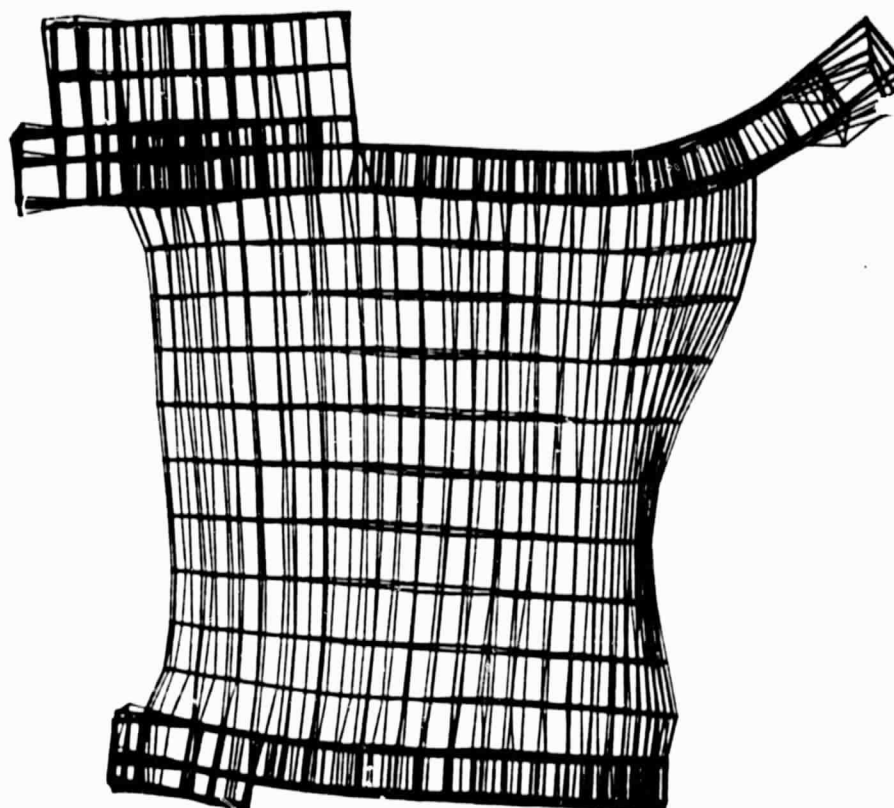


Fig. 3-29 Model F2, Mode 7, Freq 21334

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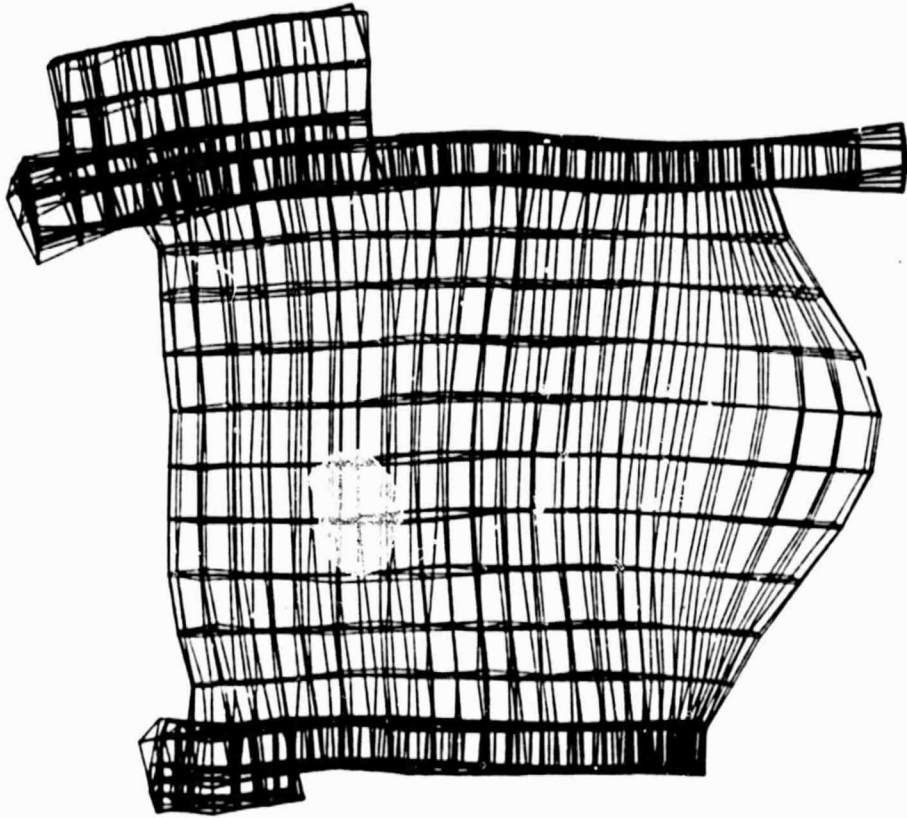


Fig. 3-30 Model F2, Mode 8, Freq 26211

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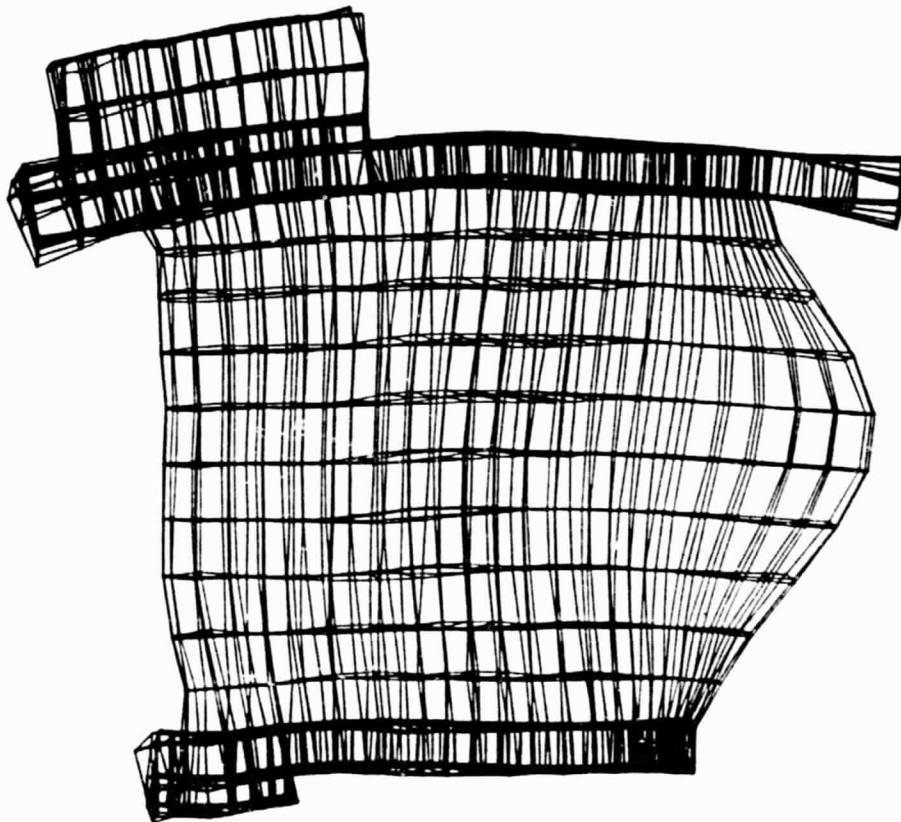


Fig. 3-31 Model F2, Mode 9, Freq 27225

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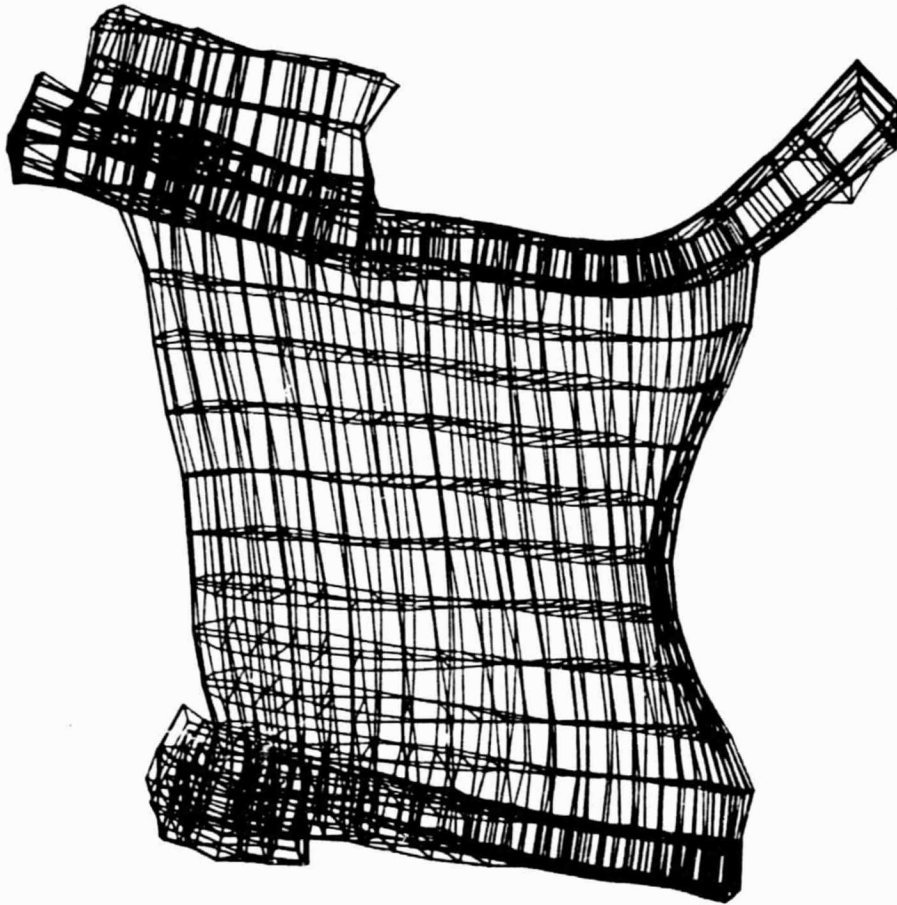


Fig. 3-32 Model F2, Mode 10, Freq 30403

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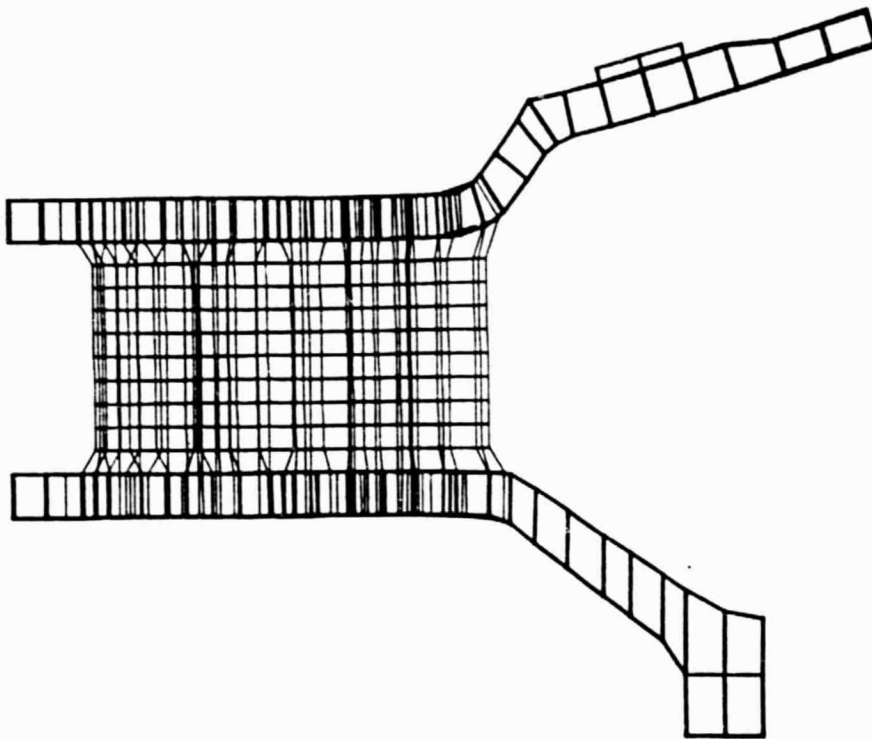


Fig. 3-33 Model 01, Mode 1, Freq 3262

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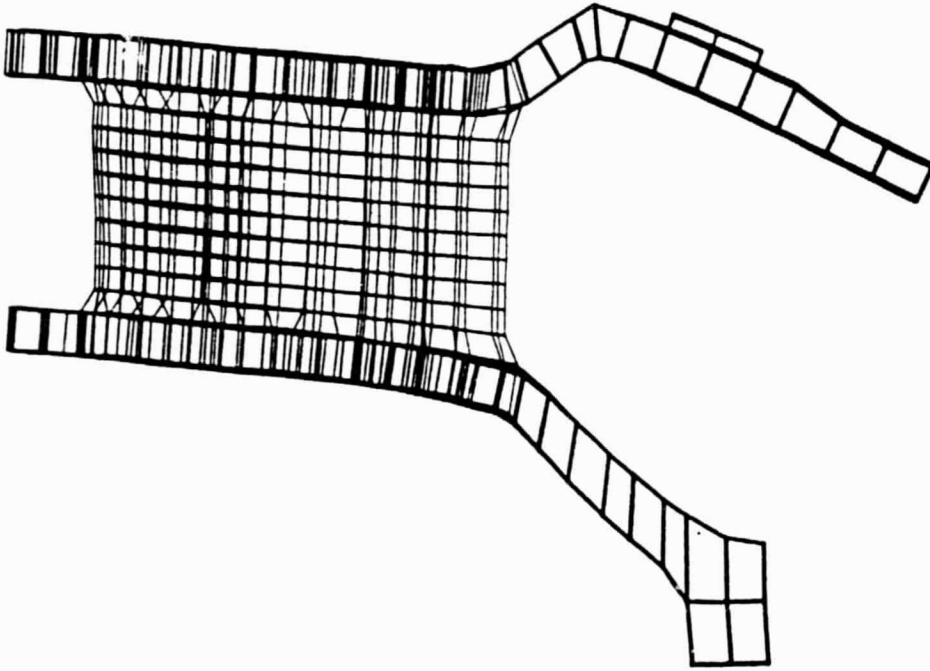


Fig. 3-34 Model 01, Mode 2, Freq 5445

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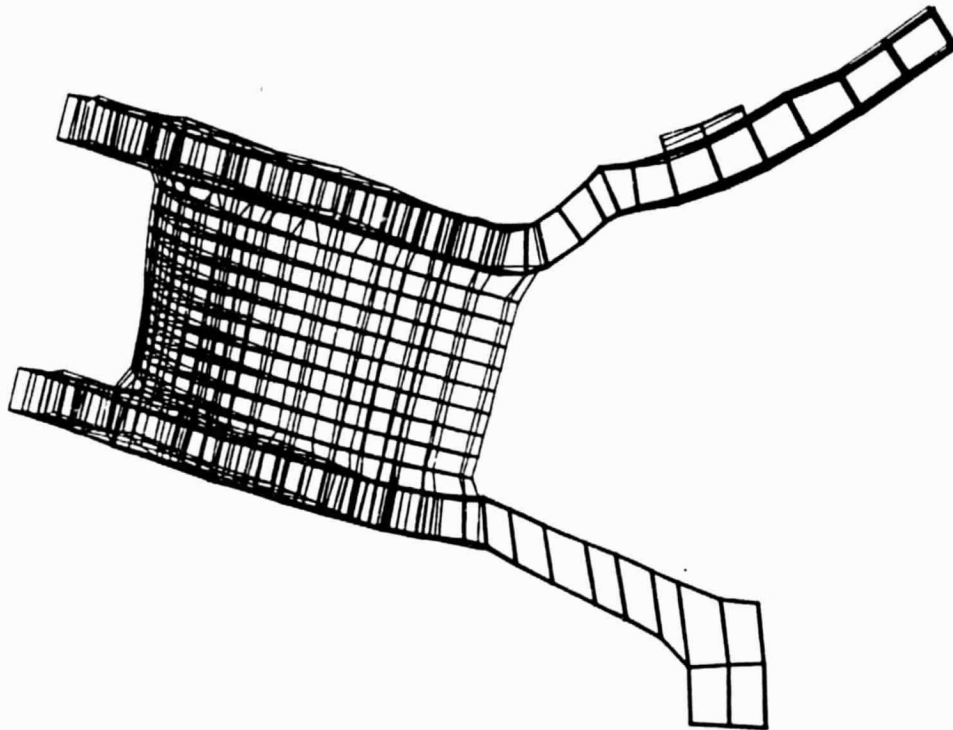


Fig. 3-35 Model 01, Mode 3, Freq 10777

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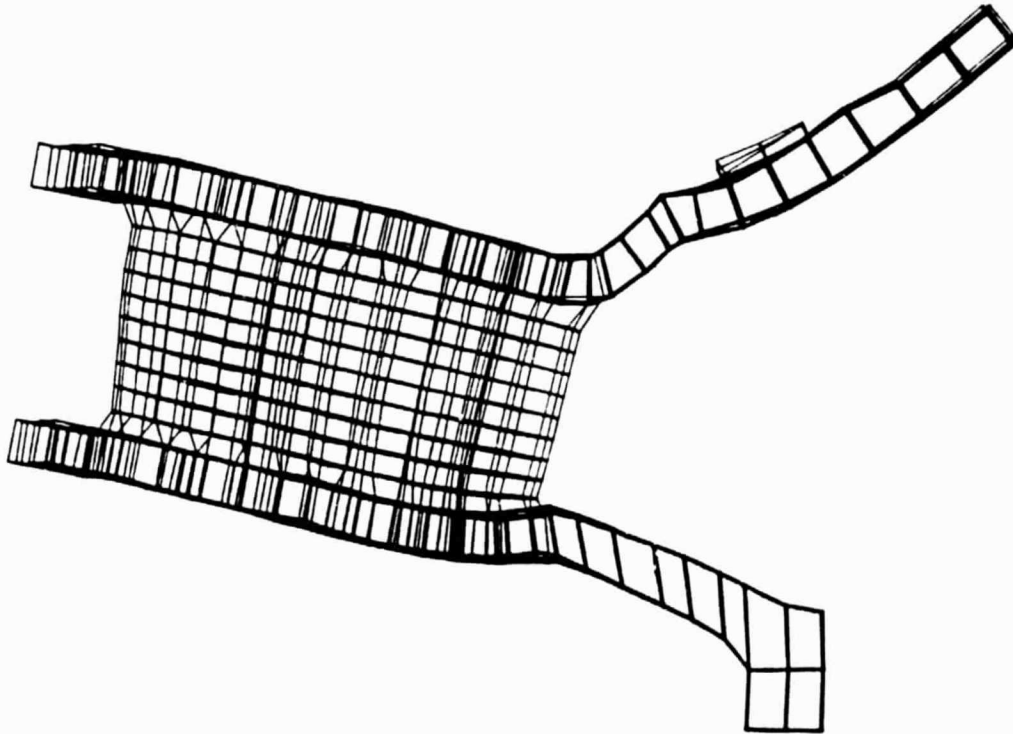


Fig. 3-36 Model 01, Mode 4, Freq 11049

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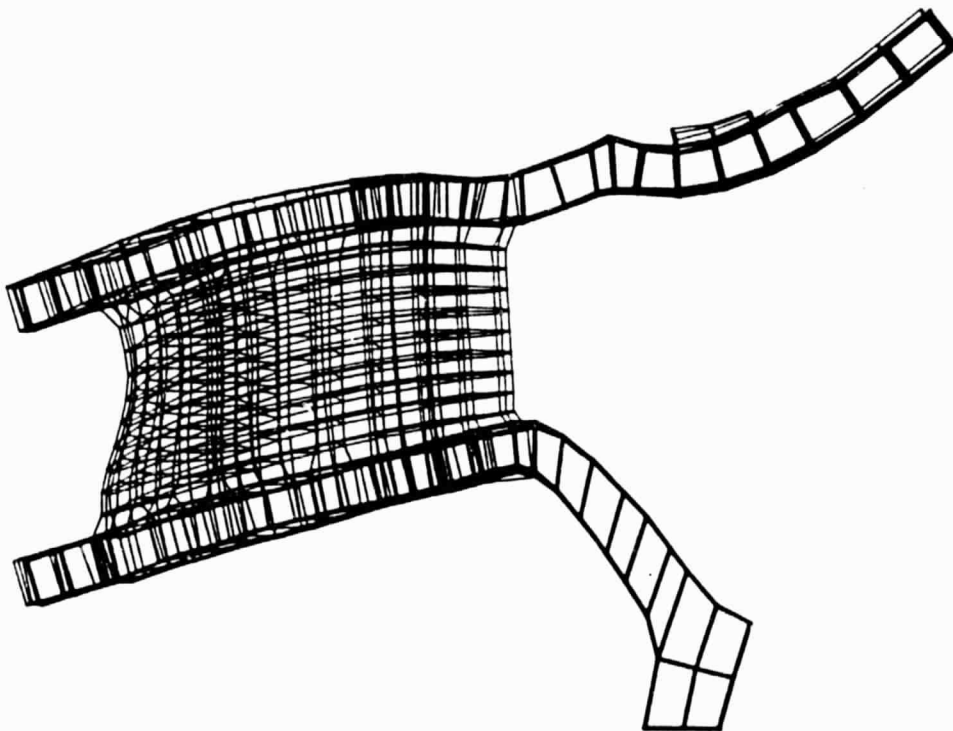


Fig. 3-37 Model 01, Mode 5, Freq 14505

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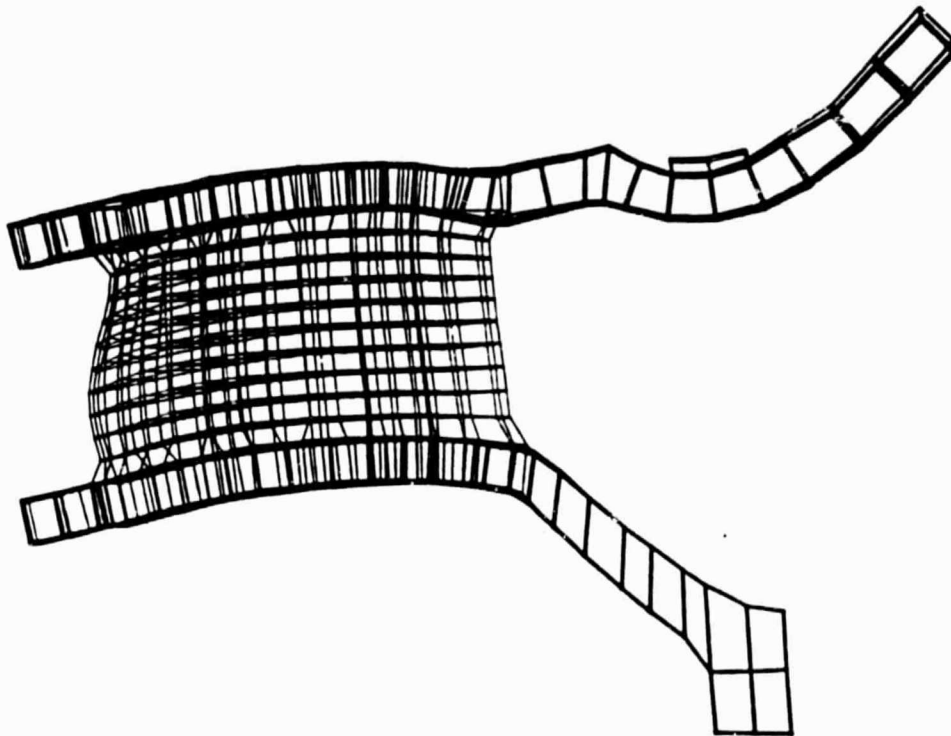


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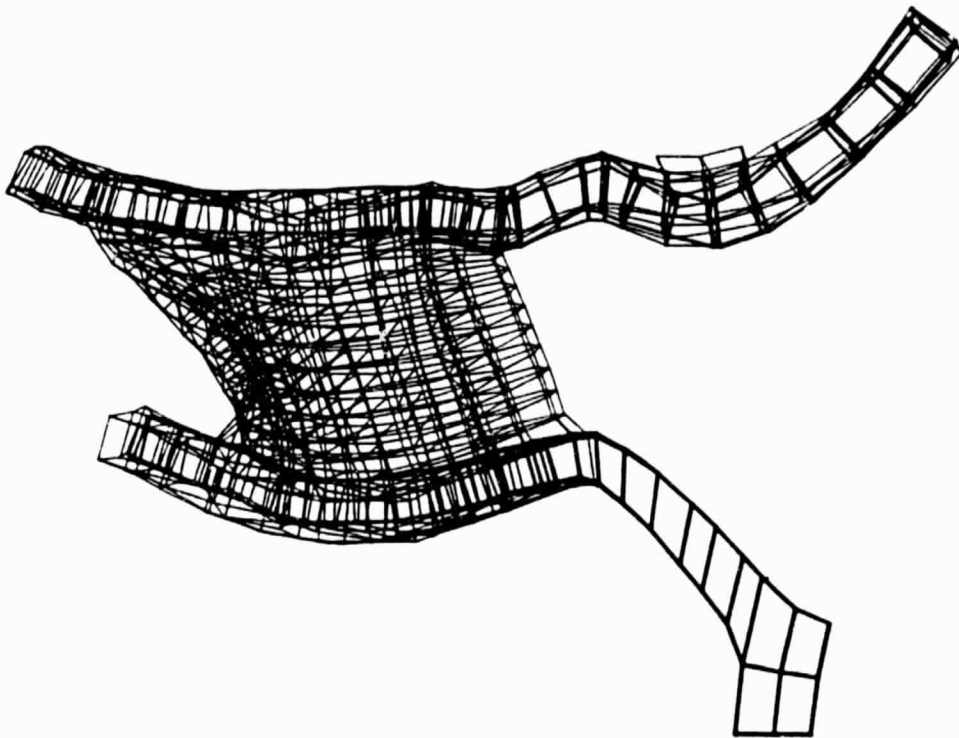


Fig. 3-39 Model 01, Mode 7, Freq 23895

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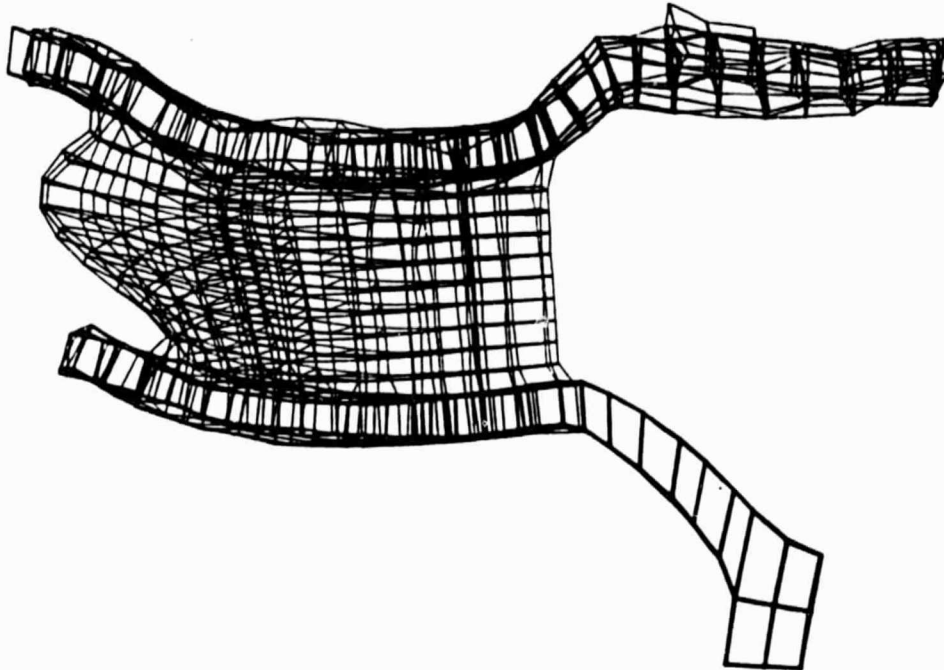


Fig. 3-40 Model 01, Mode 8, Freq 28514

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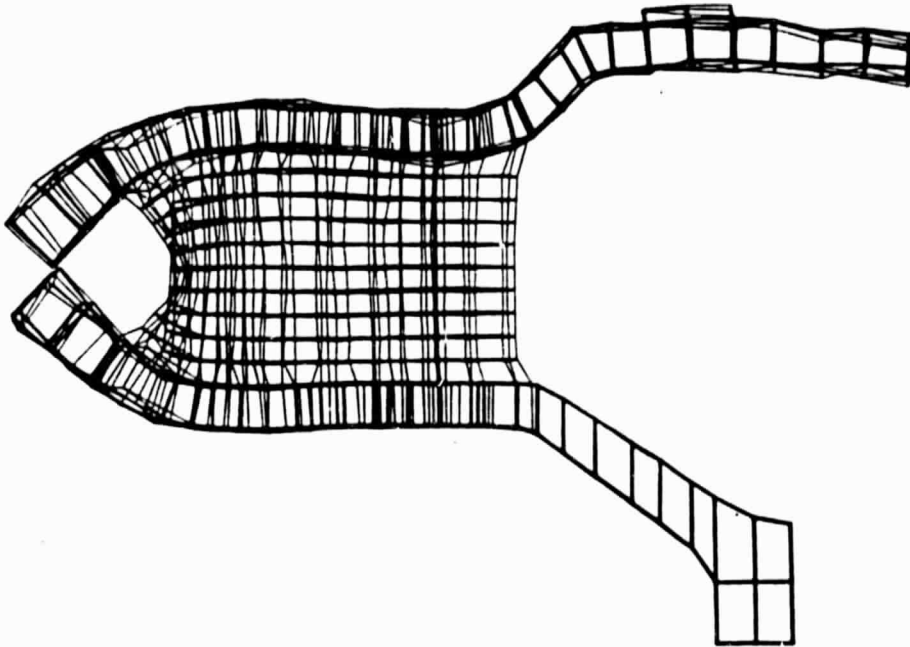


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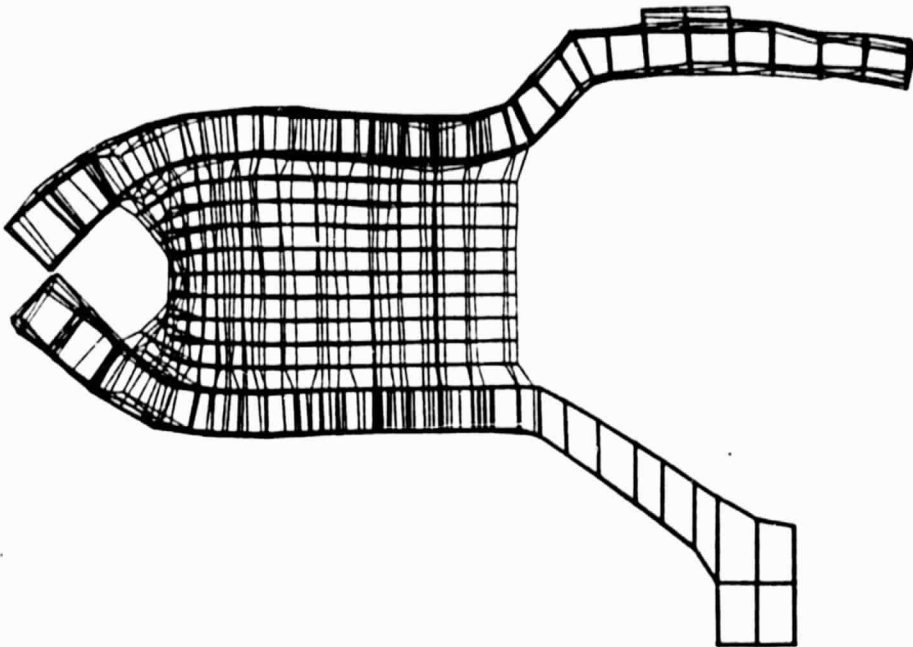


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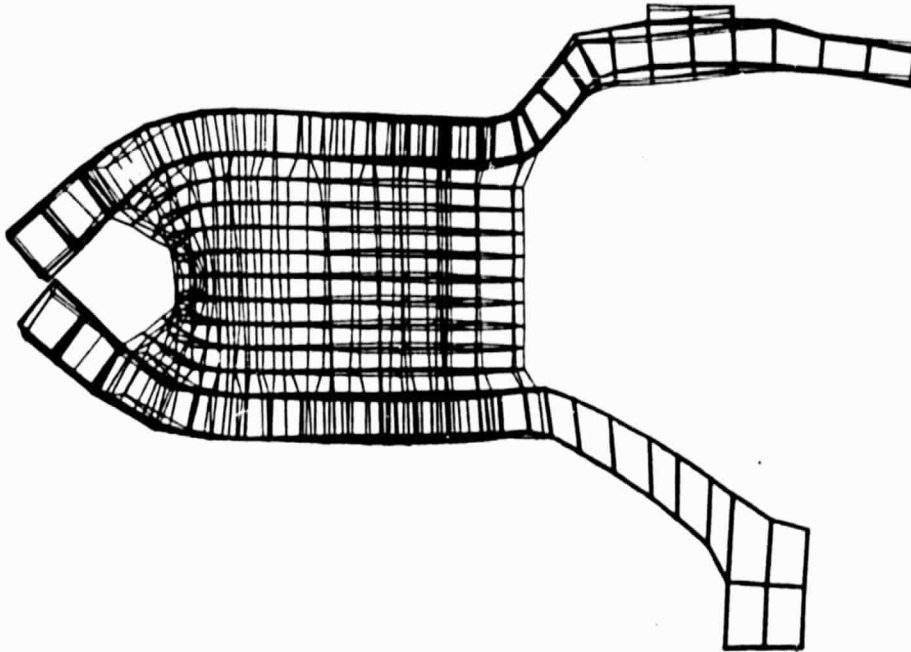


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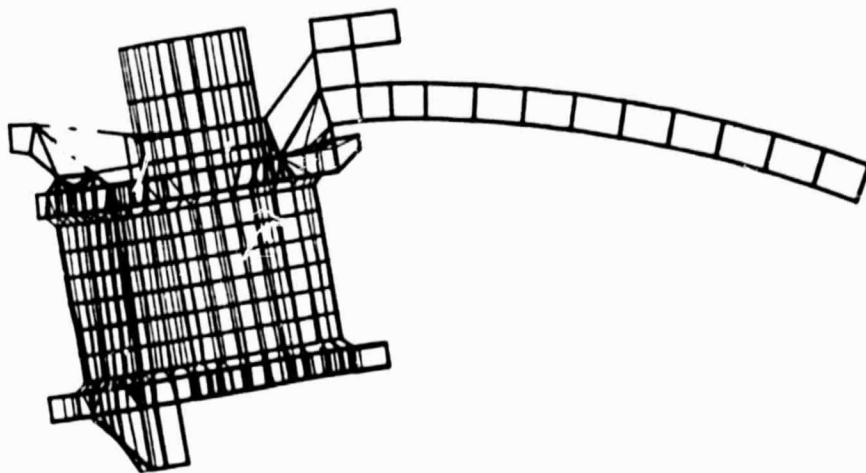


Fig. 3-44 Model 02, Mode 1, Freq 3634

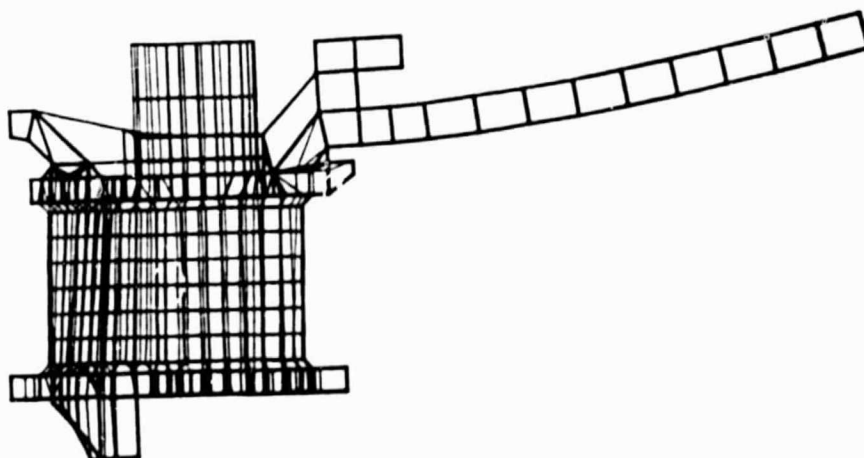


Fig. 3-45 Model 02, Mode 2, Freq 5006

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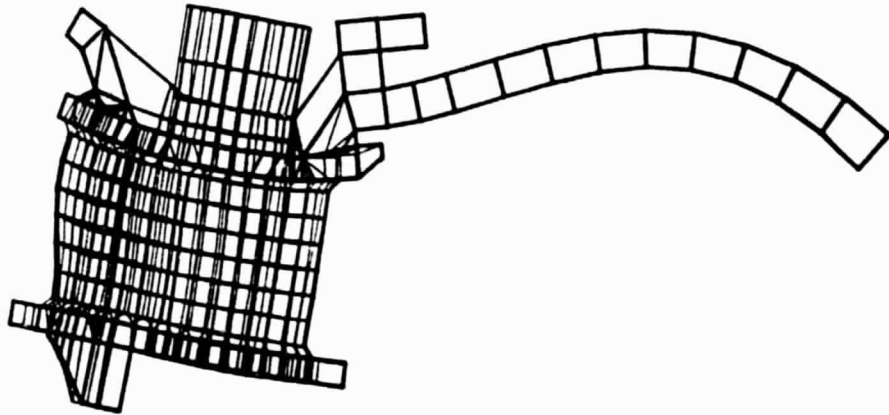


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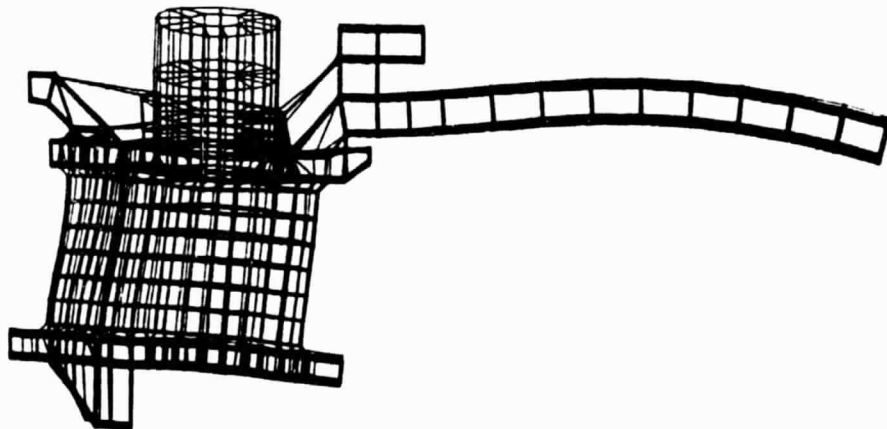


Fig. 3-47 Model 02, Mode 4, Freq 7562

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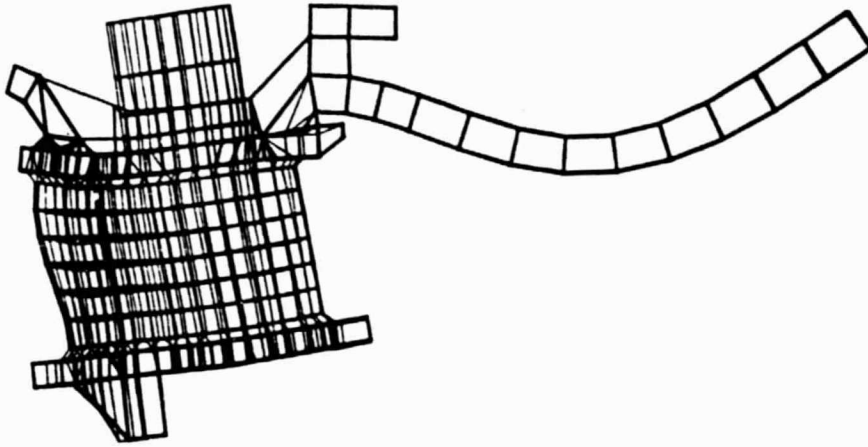


Fig. 3-48 Model 02, Mode 5, Freq 9176

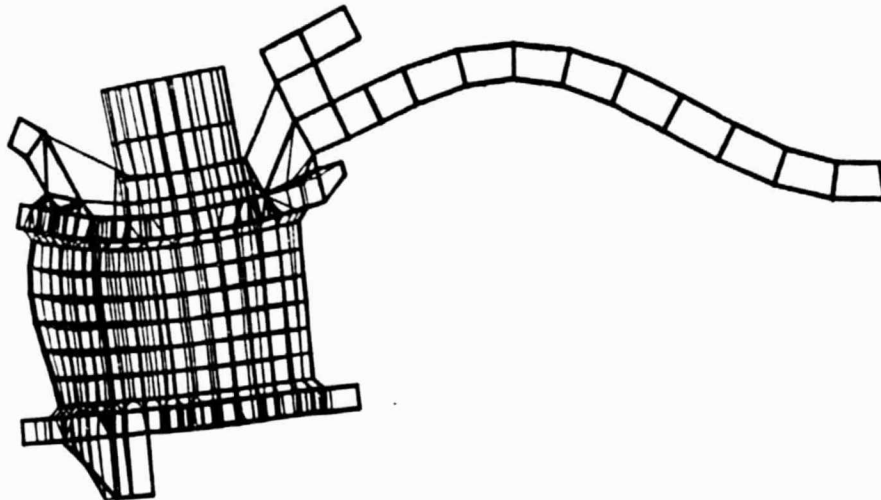


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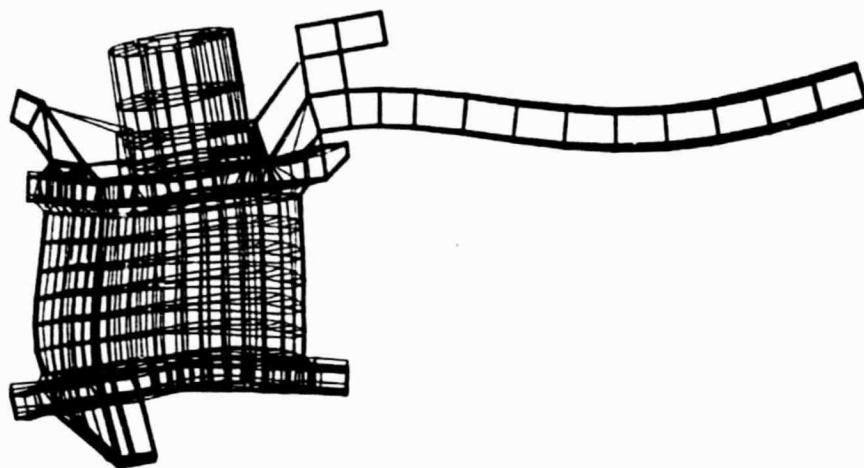


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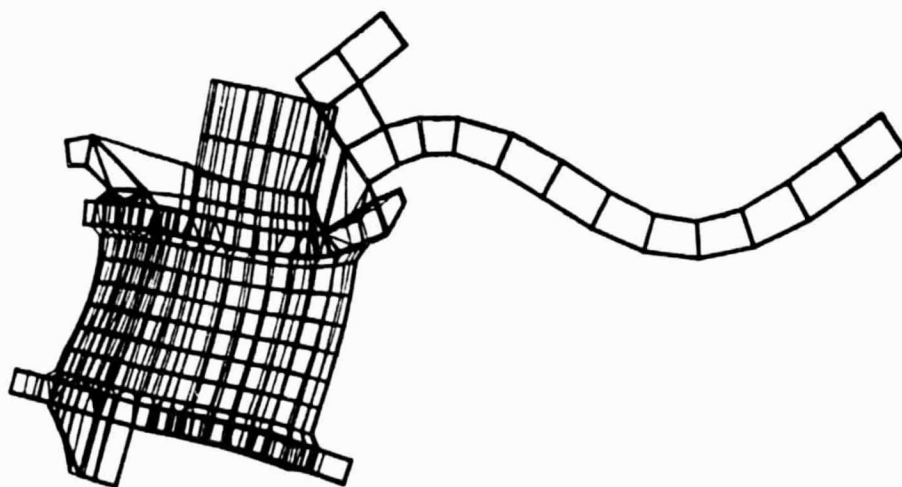


Fig. 3-51 Model 02, Mode 8, Freq 15554

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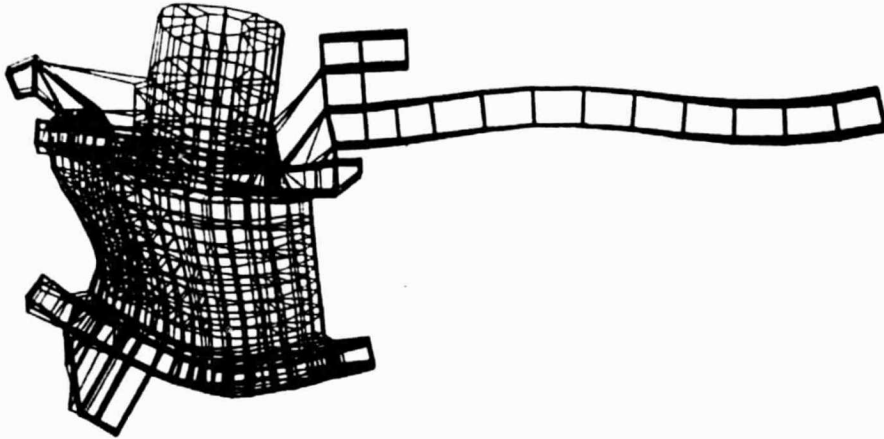


Fig. 3-52 Model 02, Mode 9, Freq 20837

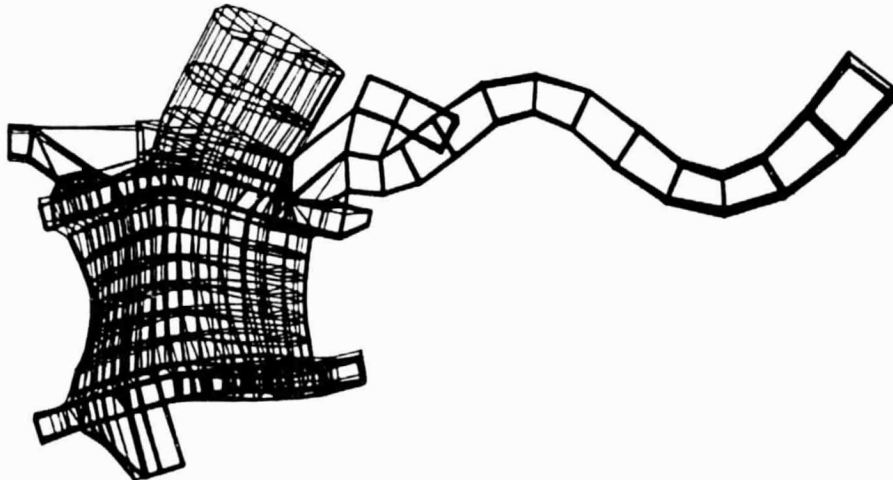


Fig. 3-53 Model 02, Mode 10, Freq 24911

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Fig. 3-54 Model 02, Mode 11, Freq 25737

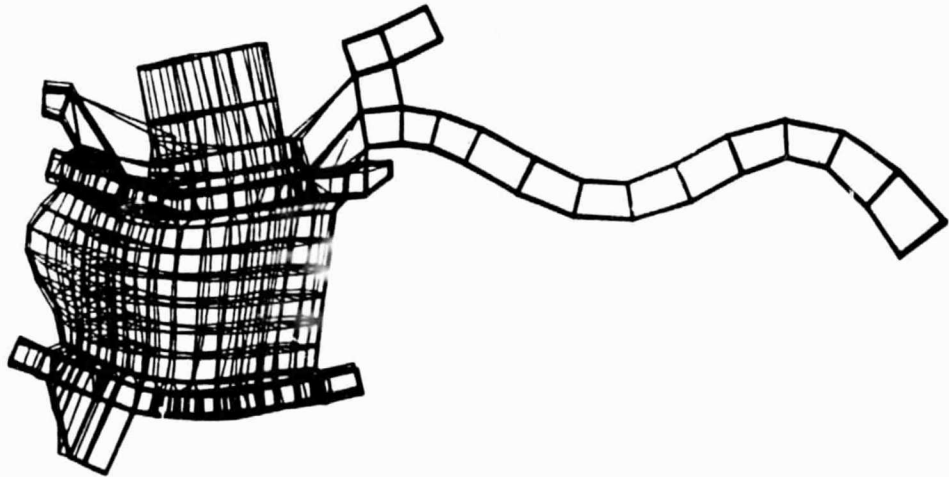


Fig. 3-55 Model 02, Mode 12, Freq 26562

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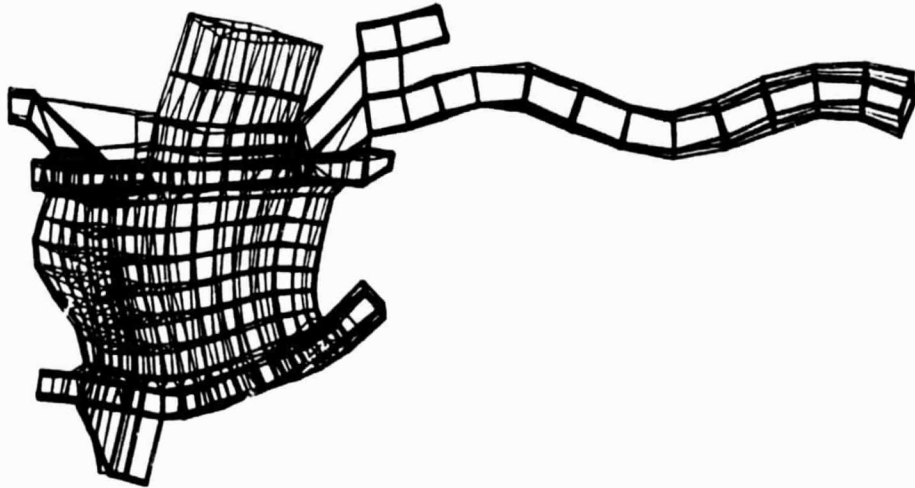


Fig. 3-56 Model 02, Mode 13, Freq 30007